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Administration

Sensor Systems For Monitoring Maglev Guideway Structures

National Maglev Initiative
Washington, DC 20590

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16. Abstract

This report is an assessment of the technologies available for continuous monitoring of the physical condition and structural integrity of maglev guideways. The detection of obstructions on the guideway is not included.

No particular guideway design is assumed, other than that the largest part of the system will consist of repetitive reinforced concrete structures, probably elevated, that are aligned with close tolerances. It is assumed that the guideway is to be monitored for the correct alignment of the sections, any unusual vibrations or motions, detection of catastrophic failure, and possibly accumulation of ice and snow.

The technologies covered are acoustic emission monitoring (a passive acoustic method of listening for crack growth or other unusual structure borne sound), infrared and visible light monitoring (ranging from cameras to displacement sensors), ultrasonics (for vibration, displacement, snow and ice), microwave monitors (for vibration and displacement sensors), and fiber optics (for networks of strain gauges).

It is the conclusion of this report that the technologies described are sufficiently mature to meet the requirements. Any particular application will certainly need development, and some may need extensive development, but the basic capabilities are there.

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METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in.) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectares (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gr)
1 pound (lb) = .45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

$[(x-32)(5/9)]$ °F = y°C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (kn^2) = 0.4 square mile (sq mi, mi^2)
1 hectare (he) = 10,000 square meters (m^2) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gr) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg) = 1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

TEMPERATURE (EXACT)

$[(9/5)y + 32]$ °C = x °F

QUICK INCH-CENTIMETER LENGTH CONVERSION

INCHES: 0 1 2 3 4 5 6 7 8 9 10

CENTIMETERS: 0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25

25.40

QUICK FAHRENHEIT-CELSIUS TEMPERATURE CONVERSION

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NBS Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50. SD Catalog No. C13 10286.

LEGAL NOTICE

EXECUTIVE SUMMARY

This report is an assessment of the technologies available for continuous monitoring of the physical condition and structural integrity of maglev guideways. No particular guideway design is assumed, other than that the largest part of the system will consist of repetitive reinforced concrete structures, probably elevated, that are aligned with close tolerances. It is assumed that the guideway is to be monitored for the correct alignment of the sections, any unusual vibrations or motions, detection of catastrophic failure, and possibly accumulation of ice and snow. It is also assumed that, in addition to instantly detecting any unsafe condition, it will be desirable for the system to detect and track gradual changes, to be fixed by preventive maintenance, rather than simply reporting that something is suddenly out of tolerance.

The technologies are assessed at their current levels of capability. The only further development needed for Maglev applications will be adaptation of current devices or systems for the particular circumstances. This does not mean that the technologies may not improve, but the systems presented in this report do not rely on extensions of the technologies.

It is the conclusion of this report that the technologies described are sufficiently mature to meet the requirements. Any particular application will certainly need development, and some may need extensive development, but the basic capabilities are there. Depending on the needs of the guideway designer or system operators, almost any level of monitoring is possible. The only likely limitation is cost, and this limit is probably not serious, given both the cost of the entire guideway and the continuously improving cost effectiveness of electronics and computers.

This report is intended to give the system designer a feel for the physical processes involved in each technology, the capabilities and limitations of each, and the other likely considerations and constraints in application for each monitoring system. It is not intended to provide a detailed design for any particular monitoring system, but rather to let the guideway system designer and the mechanical designer know what they can expect from the monitoring system designer.

The technologies covered are acoustic emission monitoring (a passive acoustic method of listening for crack growth or other unusual structure borne sound), infrared and visible light monitoring (ranging from cameras to displacement sensors), ultrasonics (for vibration, displacement, snow and ice), microwave monitors (for vibration and displacement sensors), and fiber optics (for networks of strain gauges).

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Introduction

A design for a prototype maglev guideway system has not yet been selected, but some things are becoming accepted as probable features of any design. Most of the guideway will probably be elevated. Its construction will be reinforced concrete, using techniques similar to bridge construction. It will consist of segments supported on piers, with close tolerances on the alignment of the sections.

The current plans and cost estimates show that, for reasonable economics, the system must be heavily used. There will be little room for redundancy in routes, so any down time for repairs will cause significant loss of revenues for the system operator and inconvenience for the users.

The system will be subject to visual inspection near stations, where anything unusual is likely to be noticed, and there will probably be specially instrumented vehicles to measure the ride motions. The real problem with monitoring guideway structural integrity and physical condition will occur on the high speed sections between cities, where the chances for casual observation of damage are least and consequences of failure or misalignment are greatest.

This report has a single objective: the assessment of current sensor technologies that might be used to continuously monitor the physical condition and structural integrity of the maglev guideway system. On-board systems and obstacle detection systems are specifically not included. The functions that may be carried out by systems using the technologies covered in this report are the instant location and reporting of a catastrophic failure, the location and reporting of alignments out of tolerance, reporting gradual changes in alignment or dynamical response of the structure in order to allow scheduled preventive maintenance, signs of accumulating damage such as cracking of the structure, and the accumulation of snow or ice on the guideway.

The various sensor technologies are covered in the following 5 sections. There is one section each for acoustic emission monitoring, infrared and visible light devices, ultrasonic sensors, microwave devices, and fiber optic systems. Each of these technologies is analyzed in terms of physical processes involved, capabilities, limitations, environmental sensitivities, etc. Figure 1 is a chart showing a matrix of the technologies, the evaluation criteria, and the section of the report where the corresponding information may be found. Section 6 is a summary, comparing the various possible uses of the systems and their advantages and disadvantages.

The report is intended to be useful in selecting monitoring systems for any of a variety of possible guideway designs. Therefore the sensor systems are described rather broadly. There are no complete system designs. However, within the constraints given, a detailed system design is a straightforward development project. There will likely be some testing necessary on a prototype guideway, and some of the development work may be extensive for some systems, but there are no requirements for further research. The technologies are sufficiently mature for the applications described; none of the technologies is being pushed into new or speculative applications.

	Acoustic Emission	Infrared Sensors	Ultrasonic Sensors	Microwave Sensors	Fiber Optics
Pysical Processes	1.1	2.1	3.1	4.1	5.1
Capabilities	1.2	2.2	3.2	4.2	5.2
Limitations	1.3	2.3	3.3	4.3	5.3
Environmental Sensitivities	1.4	2.4	3.4	4.4	5.4
Reliability	1.5	2.5	3.5	4.5	5.5
Costs	1.6	2.6	3.6	4.6	5.6
Data Handling	1.7	2.7	3.7	4.7	5.7
Redundancy of Coverage	1.8	2.8	3.8	4.8	5.8

Figure 1 -- Analysis Matrix

1.0 Acoustic Emission Monitoring (Passive Ultrasonic Technique)

All manufactured materials, to some degree, possess inherent inhomogeneities and structural anomalies. In most cases, such defects generally do not produce significant effects on the overall structural integrity of the material under normal operating conditions. However, it is an observed phenomenon that certain discontinuities have a tendency to grow in a time dependent fashion, especially in cases where a given load is cyclically applied to a structure. In such cases, over extended periods of service, once non-critical flaws can grow to a size where the overall integrity of a structure becomes jeopardized.

When sufficient stress is applied to a structure possessing a flaw or discontinuity, the flaw has a tendency to propagate or grow. The growth generally occurs in bursts. Stresses gradually build up to a point capable of promoting defect extension, the growth then occurs rapidly, and finally the stresses are redistributed. As increasing stress is applied to the structure, this process continues until ultimately the structure fails.

During the bursts associated with crack growth in a material, the rapid release of energy generates stress waves that originate at the crack source and propagate diametrically throughout the structure. Dubbed acoustic emissions (AE), such stress waves can be detected by highly sensitive transducers attached to the structure. Once detected, information derived from sophisticated electronic AE processing units can be used to evaluate and locate the sources of the emissions.

1.1 Physical Process

When a solid structure is subject to a stress, there is a resulting strain. If that strain exceeds the elastic limit of the material at any point, the material will crack or be permanently deformed at that point. The cracking or deformation is accompanied by a release of energy, and some of that energy is generally propagated throughout the structure as sound waves.

In many cases the sound can be heard by a nearby observer. The sounds of glass breaking or wood cracking are common examples. Considerably greater sensitivity is possible if a piezoelectric sensor is attached directly to the structure, because very little of the sound emitted is coupled to the air; most of the sound energy is dissipated within the structural material.

The coupling of sound from one material to another, and the transmission through the interface, can be calculated from the acoustic impedances of the materials. When sound in a material with impedance z_1 is normally incident on an interface with material having impedance z_2, the fractional power reflected is

$$P_R = (z_1 - z_2)^2/(z_1 + z_2)^2$$

and the fractional power transmitted is

$$P_T = 4z_1z_2/(z_1 + z_2)^2.$$

The acoustic impedance of any material is the product of the density and the sound velocity in that material. Steel has a density of 7.9×10^3 kg/m^3 and a longitudinal wave velocity of 5.9×10^3 m/sec, giving an impedance of 46×10^6 kg/m^{2}sec. Air has a density of 1.2 kg/m^3 and a sound velocity of 340 m/sec, giving an impedance of 408 kg/m^{2}sec. From the equations above, at a steel-air interface, the reflected sound fraction is 0.99998 and the transmitted power is 0.00002. This is the reason a good bell will ring long after it is struck. The energy of the vibrations is lost through the mounting and by internal dissipation. Almost no energy is lost to the air.

For other solid materials, the results are similar. The densities and sound velocities may vary by a factor of 2 or 3, but sound coupling from one solid to another will be much greater than from a solid to the air. Piezoelectric transducers are solids and have acoustic impedances closely matched to solid structures, so they have much better sensitivities to structure borne sound than a microphone which depends on sound transmission through air. These transducers are typically attached with epoxy, for a solid bond, although brazing, bolts, springs, and magnets can also be used for attachment. They can have wide bandwidth, up to 1 MHz or more, to capture more of the sound energy and provide good source location.

The sound sources of greatest interest are growing cracks. As a crack grows, the front advances in steps, as individual grains or grain interfaces suddenly rupture. These microcracking events produce sound waves which are essentially impulses, containing components at all frequencies with wavelengths longer than the size of the source. The shorter wavelengths are similar in size to the basic grain structure of the material, and are quickly attenuated by scattering, but frequencies of hundreds of kilohertz will propagate long distances in many materials.

Because of the high bandwidth, it is possible in many applications to determine the arrival time of the pulse within one microsecond or better. When this is done for several sensors, the source of the sound emission may be determined within millimeters. For reasons explained below, this precision of source location is not practical over the distances involved in Maglev applications, if the entire structure is to be monitored. With sensors located every 50 to 100 feet it will be possible to locate sources accurately enough for more detailed study later. In most cases, a pattern of steadily increasing acoustic emission occurs well before failure occurs.

The reason for loss of source location accuracy is loss of timing accuracy. This happens for a number of reasons. First, the loss of high frequency components and overall loss of amplitude of the signal produces uncertainty in detection and timing, as the wavefront becomes less sharp. The rate of attenuation of sound propagating through a solid is a function of frequency. For the frequencies of interest in acoustic emission, the attenuation is caused by scattering from inhomogeneities in the material and is inversely proportional to the square of the frequency. This attenuation is a dissipation of the energy carried by the sound wave, and is distinct from the loss in amplitude caused by the spreading of the wave with increased distance from the source.

When sound waves leave a small source embedded in the structure, they decrease in power with the square of the distance. If the waves are traveling in a plate, so that they can only spread out in two dimensions rather than three, they decrease linearly with distance. And if they are traveling in a rail or column, the propagation is one dimensional and there is no decrease with distance (other than the attenuation described above).

Another factor contributing to a loss of amplitude of the noise pulses is pulse spreading. Because the attenuation is a function of frequency, the wave velocity is also a function of frequency, which spreads the pulse over time. A larger effect comes from the nature of sound propagation in structures. The sound may travel as longitudinal, shear, surface, or plate waves, or other modes caused by more complex boundary conditions. All these modes travel with different velocities, and at each interaction at a surface or discontinuity the energy is coupled between modes. This results in a continuous widening of the pulse and reduction in peak amplitude. For example, a microsecond pulse traveling in a steel rail, after a distance of 10 meters, arrives as a burst of sound with a duration of about 1 millisecond, with a peak amplitude near the middle of the burst.

In addition to the loss of location accuracy, the attenuation also leads to a loss of detectability. Because of material variations and unknown geometry, and unknown background noise levels, the best sensor spacing can't be determined until the guideway design is complete and a prototype has been constructed.

It is obvious that the application of AE testing requires subjecting the test material to some stressing mechanism. In the case of the Maglev guideway structure, the cyclic loading resulting from subsequent train passes over a given area will provide the stress. It has been proven that, following initial loading of a structure, subsequent repeated loadings with identical stresses produce no appreciable AE activity. However, in the event of discontinuity growth during a working period, subsequent loading will subject the material at the discontinuity to higher stresses than before and the discontinuity will emit sound. Emission during subsequent loadings of a structure is therefore a measure of damage experienced during the preceding working period. In light of this, AE testing should provide an excellent global and semi-continuous indication (based on frequency of train passage) of guideway physical conditions.

1.2 Capabilities

Acoustic emission examination is a rapidly maturing nondestructive testing method with demonstrated capabilities for monitoring structural integrity. Acoustic emission differs from most other nondestructive methods in two significant respects. First, the energy that is detected is released from within the test object rather than being supplied by the nondestructive method, as in ultrasonics or radiography. Second, the acoustic emission method is only capable of detecting the dynamic processes associated with the degradation of structural integrity; static discontinuities won't generate AE. With respect to this, latent discontinuities that enlarge under load and are active sources of acoustic emission by virtue of their size, location, or orientation are also probably the most likely to be significant in terms of structural integrity. Additionally, stresses necessary for the promotion of discontinuity growth in the structure can many times be derived from loads present within the normal operating system (e.g., Maglev train passages).

A major advantage of acoustic emission testing is the fact that it is a global inspection technique. Since AE wavefronts propagate radially away from their source, AE sensors located anywhere on the structure should, theoretically, be sensitive to any discontinuity growth anywhere within the structure (provided attenuation losses aren't severe). Thus, no prior knowledge of structural defects such as probable location or orientation is necessary.

In relation to this capability is the applicability of AE testing to structures with only limited access. Since the location of AE sensors with respect to flaw locations is not critical, discontinuities may be detected with AE that are inaccessible to other NDE methods.

Modern AE test systems are also impressive from a sensitivity and performance standpoint. Depending on a given structure's naturally occurring background noise levels, modern AE sensors can be sensitive to quick flaw displacements as small as 4×10^{-11} cm. Coupled with this impressive sensitivity is the capability of some systems to process up to 100,000 acoustic emission events per second.

In addition to mere AE detection, most modern AE systems provide source location capabilities. By calculating differences in arrival times of AE wavefronts at various individual sensors placed on a test object, triangulation algorithms can be utilized to locate the actual sources of acoustic emissions. Depending on application requirements, including desired location accuracies, rate of data acquisition, and costs, a wide variety of source location algorithms of varying complexities is available.

1.3 Limitations

As mentioned, acoustic emission testing is a passive technique relying upon the dynamic processes associated with the degradation of a structure to enable discontinuity detection. Static discontinuities, no matter what size, will not produce detectable acoustic emissions. On the one hand, it inevitably generates concern when an NDE technique can potentially overlook an obvious discontinuity in a structure. On the other hand, however, latent discontinuities, while generating no acoustic emissions, should pose no threat to overall structural integrity; an inactive flaw does not jeopardize integrity or promote structural failure.

The success of an acoustic emission test, to a large extent, depends upon the degree or measure of how well discrimination is carried out between relevant acoustic emission and noise sources. Noise sources are extraneous or interfering acoustic signals carrying no data of interest. The sensitivity of an AE system to relevant emissions is indirectly related to the amount of uninhibitable noise sources. Noise signals may be continuous or intermittent and the source may either be internal or external to the test object. Two potential sources of acoustic noise for the guideway application are mechanical noise -- any movement of mechanical parts in contact with the guideway structure -- and electromagnetic interference (EMI) -- signals coupled to the acoustic emission instrumentation by electrical conduction or radiation. Fortunately, most acoustic noise diminishes in amplitude at typical AE monitoring frequencies ($>$100kHz). The most effective remedy for noise interference is to identify the noise sources and then remove or inhibit them.

The sensitivity of the AE sensors to the detection of discontinuity growth within the guideway depends upon the overall signal-to-noise ratio of the system. Obviously, if the acoustic noises associated with the system are minimal, then the detection threshold of the AE system can be set at a very low value - enabling sensitivity to low amplitude relevant emissions. On the other hand, if background acoustic noises are significant, the detection threshold of the system must be raised to prevent saturation of the system with noise signals. In so doing, the sensitivity of the system to low amplitude relevant emissions diminishes.

The sensitivity of the AE system to developing discontinuities is also determined by the attenuation characteristics of the guideway structure. In order to detect a relevant emission, the wavefront resulting from flaw growth must be able to propagate from the source of the emission to the AE sensor. The degree of attenuation the signal undergoes during this propagation, coupled with the severity of the aforementioned background acoustic noise levels, determines the minimum magnitude of a detectable relevant source. Consequently, attenuation losses as a function of distance from source dictate the number, resonant frequency, and spacing of AE sensors.

In AE applications involving actual source locations based on computer algorithms, the accuracy of the computed locations is, to a large degree, determined by the complexity of the structure's geometry. Geometries such as that associated with the guideway structure, where the length of the structure is very large in relation to cross-sectional area, lend themselves well to simple linear source location algorithms; linear source location algorithms typically produce some of the most accurate results. However, some of the more complex guideway cross-sections proposed may have critical areas that are not well coupled to the major longitudinal structures. These might each require their own sensors.

1.4 Environmental Sensitivities

Since the Maglev guideway structure will be exposed to many different and changing environmental conditions, the effects of those conditions on the AE sensors and monitoring system must be considered. Following are some of the conditions that potentially could produce adverse effects on the AE technique.

1.4.1 Temperature - The effects of temperature on sensor performance should be negligible. Typical state-of-the-art sensors have been shown to demonstrate excellent stability over the range of -45° to +80° C. The primary concern with temperature changes relates to the associated expansion and contraction of the guideway structure and the resulting acoustic noise generated from the rubbing and/or fretting at support interfaces. During actual monitoring, such noises will need to be identified and inhibited or ignored.

1.4.2 Precipitation - Any precipitation impinging upon the guideway structure could potentially produce acoustic noise within the structure. It is evident that the solidified forms of precipitation, being sleet and mainly hail, would produce the most acoustic noise and generate the most concern. Since the emissions resulting from these impacts are virtually indistinguishable from relevant acoustic emissions, it is obvious that overall system sensitivity may be sacrificed during adverse weather conditions. Crack growth will continue for long periods of time before failure, probably months, so short periods of high background noise should have little impact. It should be possible to identify hail storms by their extended location and lack of dependence on vehicle passage.

1.4.3 Airborne Debris - Wind-blown sand or other debris impacting the guideway structure may also produce acoustic noise. This will contribute to background noise, limiting the system's ability to detect crack growth. Like precipitation, it will be distributed over a large area, while the monitoring algorithm will be looking for localized activity during vehicle passage.

1.4.4 Magnetic Fields - The majority of acoustic emission sensors utilize piezoelectric material for the conversion of mechanical motion caused by stress waves to electrical signals. Since these sensors must be mechanically attached to the guideway, it is highly probable that they will be subjected to intense magnetic fields. The effect of magnetic fields was examined in an experiment found in Appendix A3. This experiment exposed piezoelectric sensors to a 5500 gauss field in an effort to observe any effects that the field may have on the sensor's sensitivity. The results indicated that strong magnetic fields do have an effect on piezoelectric type sensors by slightly increasing the natural frequency of the crystal as well as damping it. Although the effects measured in this experiment did not seriously hamper the ability of these sensors to operate effectively, the effects caused by intense fields such as those produced by a Maglev propulsion system are still not known.

1.5 Reliability

Fundamental requirements for a successful AE sensoring application on the guideway structure include an AE system capable of:

- operating continuously over extended periods of time with minimum maintenance
- withstanding widely varying and fluctuating environmental conditions
- providing stable results during changing background conditions
- providing mass data storage

These requirements pose no real problem for most modern state-of-the-art AE monitoring systems. There are many proven continuous on-line AE monitoring applications currently in service.

Obviously, any long term sensoring application will require some maintenance to ensure optimum test results. It is envisioned that periodic checks should be made on all system electronics and sensors to verify that no degradation in overall sensitivity or response has occurred.

Due to the harshness of the environment and other time dependent variables, long-term acoustic coupling of the AE sensors to the structure's surface could prove difficult. Sensors are often attached with glue, or mechanically attached with an acoustic couplant material such as silicone grease at the interface. These materials may degrade with time. It would be advisable to re-couple the individual sensors at determined intervals to ensure reproducible results.

1.6 Costs

Acoustic emission sensors are currently priced in the range of $150 in small quantities. Each sensor needs its own electronics package. Depending on the package and capabilities, a total cost of $500 per sensor in large quantities is probable. If the guideway is one of the simple cross-section designs, one sensor per section would be sufficient. At 20 meters per section, that would be 50 per kilometer, or $25,000/km. Double tracks, with twice as many per track, would be $100,000/km. Assuming fiber optic communications, to avoid the possible electromagnetic problems from the train, some kind of collector system would be needed as described in the fiber optics cost section.

1.7 Data Handling

AE signals are detected as noise bursts. These bursts are typically characterized as to amplitude, arrival time, duration, and number of zero crossings (count). This should probably be handled near each sensor, with results communicated to a local concentrator which could accumulate statistics for a number of local sensors. The local concentrator would handle source location and monitor sensors for defects in operation. Any changes in activity, whether crack growth or sensor failure, (or hail storm), would be determined. These results would then be passed to the central control system.

1.8 Redundancy of Coverage

For good source location, at least two sensors should pick up the sound for any single event. This also allows the easy detection of sensor failure. A lower cost alternative is to use sector location, in which only one sensor is in range to detect any event, and the event is assumed to be in the sector covered by that sensor. If a sector becomes active, more instrumentation can be added to locate the source.

2.0 Infrared and Visible Light Sensors

This section covers both infrared and visible light sensors. The sensor systems useful for Maglev will have a light source and a detector. Systems without a source are possible, such as heat detectors or TV cameras, but a light source would be needed if a camera is to function at night and no applications for a heat camera have been identified. The use of cameras for monitoring the physical condition of the guideway is questionable, because the dedication of a camera and monitor and someone to watch it for checking the alignment of each guideway section is gross overkill. Cameras might be used in monitoring for intrusion or obstructions of the guideway, but that is outside the scope of this report.

2.1 Physical Processes

Infrared (and visible) radiation sensors are theoretically electromagnetic devices, like the microwave sensors of section 4. They are differentiated from microwave sensors by the extreme shortness of the wavelengths and the extreme high frequencies involved. The short wavelength allows optical ray tracing, in which the wave propagation of the radiation can be ignored because the apertures are much larger than the wavelengths. The frequencies are much too high for electronic devices to handle, so photon interaction effects become the basis for detection and measurement.

Photon detection can be carried out by a variety of devices, but for cost and reliability semiconductor detectors are preferred. Any photon with energy greater than the semiconductor bandgap can produce free charges in the form of an electron-hole pair. Given a reasonable light intensity the pairs form a current which may be detected by the photovoltaic effect, or by producing a current in a back-biased diode, or stored as a charge in a CCD array. Photon energy is inversely proportional to wavelength; a 1 eV photon has a wavelength of 1.24 microns (near infrared), and a 2 eV photon's wavelength is 0.62 microns (visible red). Silicon has a bandgap of 1.15 eV, so it has good detection capabilities from the near infrared through the visible region. Its bandgap is also large enough that thermally excited electron-hole pairs are not a great problem. Because of the current state of development of various detectors, silicon looks like the best choice for Maglev applications.

The systems commercially available come in two varieties, laser vibrometers (light energy emitted, reflected, and returned), and laser triple beam devices (optical triangulation). Both methods rely on laser light emission to the object in question and on a return signal which is comparatively analyzed by the internal instrumentation.

The laser vibrometer works according to the basic principles of laser interferometry. It uses a visible, low-power HeNe laser source operating at 633 nm wavelength (Laser Class 2), which is split into a reference beam and an object beam. The object beam passes through another beam splitter and is focused to a point on the vibrating surface by a lens.. At a third beam splitter the backscatter from the object mixes together (interferes) with the reference beam. This mixing causes any frequency difference between the two beams to show up as an intensity modulation at the third beam splitter. The light scattered from the vibrating object experiences an instantaneous Doppler frequency shift proportional to the instantaneous velocity of the object. In order for the vibrometer to distinguish between motion toward or away from the optical head, an acousto-optic modulator (Bragg cell) is used to introduce a static 40 MHz frequency shift on one of the beams.

The laser triple beam device works according to the basic principles of optical triangulation whereby laser diode light at 780 nm wavelength (Laser Class 1) is refined by a lens and directed towards an object. The light is then diffuse-reflected from the object's surface and focused into an image on the light-receiving element by another lens tilted against the projection light axis. The distance to the object is calculated by detecting the deviation of the image focused on the light-receiving element or position sensitive device. When the reflected light is focused onto the surface of the position sensitive device, the high-resistive layer produces currents that are inversely proportional to the distance between the position of incidence light and the output electrode. These output currents are processed by the proper formulae to determine the distance to the object.

2.2 Capabilities

Very simple source-detector systems can be used to detect specific motions. These may be useful in some places, but because of their all-or-none response, they are not likely to be useful in a monitoring system designed to detect and measure the gradual changes that require preventive maintenance. They should be considered wherever a moving part's location is to be verified (like a switch) because of their noise resistance and lack of moving parts.

A commercially available laser vibrometer has the capability to measure the velocity and absolute displacement of a point on a vibrating structure in a totally non-contact manner. It can measure through windows or water, and requires no reflectors or mirrors. It features an adjustable standoff distance from 3 centimeters to 30 meters. The four velocity ranges offered are from 5 mm/sec/V to 1000 mm/sec/V (max 10 V output), each with at least 0.1 Hz to 500 kHz bandwidth and dynamic range of 80 dB. This means the detectable velocity range available is from 1 micron to 10 meters per second. The amplitude detection range is from 1 micron up to 20 centimeters.

The laser triple beam device has the capability to measure the linear displacement between itself and an object at which its semiconductor light source is aimed. The sensor is available in 2 measurement ranges, 30 to 50 mm with 30 micron resolution, and 50 to 100 mm with 150 micron resolution. Response time is 50 msec in both ranges, and the output voltage is +/- 5V. Higher powered units (+/- 8V and Class IIIb) with a response time of 2 msec, but the same measurable range and distance, are available. The response times are much faster, but resolution is slightly lower at 35 microns. When mounted with screws these sensors can resist shock of up to 10 G in each direction of X, Y, and Z, up to 5 times.

2.3 Limitations

The limitations of the laser vibrometer concerned the life of the laser unit (one year warranty from manufacturer), protection from the elements of nature, and the possible misalignment of the light with the test object which may occur over a period of time and cause increasingly lower signal-to-noise ratios. These may be overcome depending on the mounting arrangement for the unit. Other limitations to consider include the operating temperature range of 5° to 40°C, and a tolerable humidity range of 20 to 80% RH.

The laser triple beam sensor is limited somewhat by its necessity for close proximity to the test object. However, it has an operational temperature range from -15° to 50°C, and can operate in humidity from 35 to 85% RH without dew condensation. The temperature drift for the sensor section is +/- 3 mV/°C or less and for the controller section +/- 1 mV/°C or less. The relationship between distance and the analog output voltage characteristic is nearly linear, but a slight deviation exists in specific applications. These non-linear errors are related to the material of the object being detected, and the degree of error is less with objects of low reflectivity than with objects of high reflectivity such as metals.

Neither of these two types of monitoring systems would be able to provide continuous measurements along the guideway since they both offer "point measurement", but they could provide valuable spot information at strategic locations along the route at or between joints.

2.4 Environmental Sensitivities

Laser vibrometers and laser triple beam devices are highly sensitive and would require protection from the natural elements such as rain, snow, frost, and dust and dirt. Also, maintaining Laser Class 2 and 1 respectively makes these systems rather safe for the general public. The vibration tolerance of these delicate systems is not mentioned for the vibrometer and is listed as 10 to 55 Hz (one minute period) at 0.75 mm for the optical triangulation system. The effect of the electromagnetic fields generated by the Maglev vehicle on these systems needs to be closely examined. There should be no significant effect if they can be contained sufficiently and mounted directly to the guideway in a protected location to be determined after the guideway configuration has been designed.

In any optical devices, dust on the lenses or fog or snow could disable the system. This is likely to be a major deterrent to the use of any optical system.

2.5 Reliability

The ultimate reliability of these two highly accurate monitoring systems rests with the probable lifetime of specific components. The most suspect components are, of course, the HeNe laser source and semiconductor laser diode contained in their respective systems. Routine maintenance examinations of the units would consist mostly of checking light sources, alignments, and clearing away obstructions near the sensors.

2.6 Costs

The initial costs of a laser vibrometer providing the capabilities described above in Section 2.2 are approximately $40k for each unit purchased. Lower priced models starting at around $24k are available which only provide velocity measurements. It is our belief that circuitry to provide displacement data could be integrated into the base system for considerably less than the $16k difference in price. In any case, these are single unit prices. Quantities would certainly be less expensive, but would probably be the highest of any of the systems considered. The structural spacing and/or number of joints along the route will help determine the number of infrared monitoring units to be strategically located along the guideway structure. Because of their unique ability to measure small vibrations at long distances, they might be useful at critical points, and they would probably be very valuable in testing of prototype designs.

The initial cost for a laser triple beam device providing the capabilities described in Section 2.2 are approximately $1.5k for the low powered units, and $2.5k for the high powered units. Again, these are single unit prices, which makes them generally competitive with other systems. Current devices have no means of sending results to a central location. The guideway structural spacing and/or number of joints along the route will help determine the number of infrared monitoring units to be strategically located along the guideway structure.

2.7 Data Handling

The information provided by the vibration meter should be processed and summarized by a local computer before forwarding to a central system. The triangulation device provides very little information to process, but it too should be sent to a central system after processing. Assuming that several triangulation devices are used at each joint (one per direction of possible motion) they could all be monitored by a single very small computer connected to a fiber optic communications line.

2.8 Redundancy of Coverage

The laser vibrometer and the laser triple beam device, if placed at intervals along the guideway, would not offer redundant coverage from one unit to the next since they would be too far apart. It would not be cost effective to have a sufficient number of these devices to provide redundancy in the event of sensor failure. They would, however, provide excellent detection capabilities for misalignment of sections and vibration of the guideway, as well as some degree of overlapping coverage for other sensor types in the same area.

If one of the laser-based systems were to fail completely, then all of the other sensor types except AE could still detect misalignments. Vibrations could be detected by the fiber optic systems and the microwave systems.

3.0 Ultrasonic Testing

The detection and measurement of guideway deflections, gaps, and ice buildup may be achieved through the use of air-coupled, non-contacting ultrasonic transducers. This technique is commonly used for dimensional inspection and robotic control in industry.

Much of the basic theory and applications information about the use of ultrasonics is from the field of non-destructive testing. Unlike a typical non-destructive examination, where sound is transmitted into a solid or liquid, air would be used as the sound supporting medium for guideway monitoring.

3.1 Physical Process

Ultrasonic waves are typically produced with a wavelength-to-source-size ratio which is a small number. This produces propagation effects intermediate between light (small wavelength limit) and ordinary sound (long wavelength limit). The discussion in the following two paragraphs is simplified, but intended to give a feel for the physics involved.

In the near field, the sound propagates in a beam with a diameter equal to the transducer, like light from a flashlight. The length of the near field is given by $D^2/4\lambda$, where D is the diameter of the transducer (or the side of a square transducer) and λ is the wavelength. The wavelength is the velocity divided by the frequency, and the velocity is about 330 m/sec (or 13,000 inches/sec in convenient non-SI units).

In the far field, the sound spreads out like a beam from an antenna. For a square transducer, the amplitude distribution is given by $(\sin x)/x$, with $x = (\pi D \sin \theta)/\lambda$, with θ the angle from the beam axis. For a circular transducer the distribution is $(J_1(x))/x$, where J_1 is a Bessel function. In either case, a handy rule for estimating beamspread is that the free field response will be down 3 dB, and the round trip response down 6 dB, at approximately the angle $\theta = \arcsin(0.5\lambda/D)$.

Most guideway monitoring applications would require that the sound travel through the air, reflect off the surface being monitored, and then to a transducer where it is received and analyzed.

It is common that both transmitting and receiving of the ultrasonic signal can be performed by the same transducer, but some geometrical conditions may require that separate sending and receiving transducers be used. Each transducer or transducer pair would require its own pulser/receiver electronics and signal analysis microprocessor. Multiplexing is an option for multiple sensors located in close proximity to one another, but distances greater than 150-200 feet can result in significant loss of signal and noise interference without special line-driver electronics.

Air is not an ideal medium through which to propagate ultrasonic waves. It is highly attenuative at higher frequencies (> 1MHz), it has a low acoustic impedance, and the sound velocity of air can fluctuate significantly with variations in environmental conditions.

Fortunately high frequencies are not necessarily required in order to achieve highly accurate results when working in air. The accuracy of a measurement is directly related to the sound wavelength being used. The shorter the wavelength the finer the resolution of the measurement. The product of wavelength and frequency is equal to the sound velocity. Due to the relatively slow velocity of sound in air, about 330 m/sec, the high frequencies normally used in non-destructive testing (2 - 25 MHz) are not required in order to achieve very high accuracies. For example, 1 MHz sound has a wavelength of 0.33 mm.

Air is considered to be an "acoustically soft" medium. This is an indication of the low acoustic impedance associated with this medium. Acoustic impedance is defined as the product of density and the velocity of sound in that medium. In order to efficiently transmit acoustical energy from one medium to another, the media on either side of the interface should have similar acoustic impedances. If these values are grossly dissimilar the acoustic wave will reflect off the boundary instead of transmitting through it. This problem can be significant when using air as a couplant. Air-coupled transducers are relatively inefficient since the active element (high acoustic impedance) must transmit acoustic energy into air. As a worst-case example, the round trip coupling of sound from steel to air and back to steel has about 100 dB loss. (This means that steel faced transducers are not very useful in this application). Special impedance matching layers may be used in order to minimize this effect, if continuous wave signals are to be transmitted. These materials typically are designed to have an acoustic impedance near the geometric mean of the acoustic element and the sound supporting medium, and a thickness that is a multiple of half the wavelength. Impedance matching layers do not help pulse transmission because the impedance matching effect is a standing wave phenomenon. Impedance effects on reflection are described in more detail, with equations, in section 1.1, physical processes of acoustic emission.

Transducers intended for use in air are mostly available in two different configurations, utilizing either piezoelectric or electrostatic (capacitor type) elements. The operation of piezoelectric transducers is based upon the coupling between the strain of the material and the voltage across it. In transmission, a voltage pulse to the piezoelectric element causes a sudden stress in the material. The resulting strains are transformed into pressure waves which typically travel through a coupling medium into the material of interest. In reception, the arriving waves cause strains of the material which cause voltages that can be measured.

An electrostatic transducer consists of a special foil stretched over a grooved metallic back plate, forming a capacitor. An electric pulse produces an electrostatic force on the foil which causes movement, producing a sound wave. An arriving sound wave moves the foil, changing the capacitance, which is detected electronically.

Guideway deflections, gaps and ice build-up can all affect the time required to reflect sound off an appropriate surface and back to a transducer. Guideway deflections would be detected by placing the transducer at a stationary position, independent of the guideway, with ultrasound being reflected off a guideway surface. Any movement of the guideway that involves displacements toward or away from the sensor position will affect the travel time of the ultrasound. Similarly, gaps forming at expansion joints can be monitored by mounting a sensor onto the guideway on one side of the joint and reflecting off a designated surface on the opposite side of the joint. Accurate time-of-flight measurements could be used in determining actual gap dimensions or alarms could be issued due to excessive separation. Ice and snow build-up measurements would be determined by reflecting ultrasound off a horizontal surface in close proximity of the guideway or the guideway itself.

An alternate approach to measuring ice build-up may be accomplished by coupling piezoelectric transducers to the opposite surface of the guideway. Air coupled transducers would not be used for this application since the ultrasound would be coupled directly into the steel. These contact transducers are manufactured with wear faces that are more closely matched to the acoustic impedance of steel. Ultrasound would travel through both the thickness of the guideway surface and the guideway/ice interface. The ultrasound would reflect off the outer surface of the ice and propagate back through the ice, interface, and guideway material to the transducer. Ice thickness would be determined by measuring the difference in arrival times of both the ice interface signal and the guideway/ice interface signal.

3.2 Capabilities

Air coupled sensors have the capability to measure guideway displacements and ice buildup with very high accuracies. The actual accuracy that can be achieved from an air coupled sensor is ultimately dependant upon the frequency of the ultrasound being produced by the sensor. Commercially available ultrasonic ranging or proximity systems have stated accuracies that range from approximately 0.025 mm (0.001") to 1% of reflector distance. Similarly, these sensors can be located as close to the reflector as 10 cm (2.5") or as far away as 12 m (40 feet). It should be noted that accuracy decreases with an increase in sensor-target separation. This is due to the relatively large sound attenuation associated with the higher sound frequencies in air. This results in the necessity of using lower frequency sensors for the larger sensor-target distances. Consequently, lower frequency results in a larger wavelength thereby reducing measurement accuracy. Maglev applications for these sensors would most likely require sensor-target separations less than 1.5 m (5 feet). In this case the best expected accuracy would be approximately 1.5 mm (0.06").

The successful deployment of a structure coupled ultrasonic ice thickness gage is highly dependant upon design of the guideway. It is possible that geometrical factors could make the use of such a sensor impossible. This sensor would need to be coupled to a surface that is parallel to the horizontal surface being monitored for ice build up. It is preferable that the material be metal, steel or aluminum, as losses and scattering in concrete can be severe. If nothing suitable is in the guideway structure, a horizontal plate located somewhere in the right-of-way could be used. Rate of ice build-up and melting would have to be representative of the areas where ice is a concern.

The thickness of the material separating the coupled transducer from the horizontal iced surface should not be less than approximately 3 cm (assuming a maximum ice thickness of 2 cm). If this material were thinner, then the multiple reflection associated with the metal path could arrive at the same time as the multiple reflections associated with a thick ice layer. It should be stressed that this technique is capable of measuring ice thickness only. Since the ultrasound must propagate through the medium being evaluated, conditions such as snow, sleet, dirt etc., cannot be tested simply because they will not support high frequency wave propagation. The experiment found in Appendix A1 was performed in order to demonstrate feasibility of this technique and to determine what accuracies could be expected. Based upon the results of this study, it was estimated that accuracies on the order of +/- 0.25 mm should be achievable for a Maglev application.

Another capability is the measurement of snow and ice accumulation by air-borne ultrasonics. This would be carried out with a sensor looking down onto a horizontal surface and detecting the decreasing distance to the surface as snow accumulates. Appendix A2 contains a study of the feasibility of this. We had to simulate the snow, because unfortunately Virginia had a very mild winter this year. Any snow heavy enough to cause a problem should be detectable. The problems would be in measuring on the guideway with vehicles passing by. It might be acceptable to measure on a level surface near the guideway where the wind from the vehicle is about the same as on the guideway. This is very dependent on the guideway design selected. Snow and ice measurement could also be carried out by the same sensor used for vertical displacement, if it is assumed that real vertical displacements are adequately determined during warm periods.

3.3 Limitations

The relative orientation of an acoustic sensor to the surface from which sound is to be reflected is important, because it is rather like reflecting light from a mirror. If the same transducer is used to send and receive the sound, the surface must always remain approximately perpendicular to the propagation vector. Although the amount of angular offset that can be tolerated is dependant upon the frequency and distance of propagation, typical tolerances are 3 to 10 degrees.

Air coupled ultrasonic sensors are similar to other proximity sensors in that displacements can only be measured in one direction per sensor. Only that movement which changes the distance that the ultrasound must travel can be detected. The use of one detector at a given location will provide information concerning the component of movement in a prescribed direction. This is adequate if restraining conditions permit deflections only in that direction. It is possible that up to three sensors per location could be needed if knowledge of the movement in all three dimensions is desired.

Environmental conditions such as temperature, rain, noise, air pressure and turbulence can all affect the accuracy or effectiveness of air coupled ultrasonic transducers if not taken into consideration. Protective covers or environmentally resistant transducers can reduce any adverse effect that water can have on the operation of a sensor. Variations in velocity due to fluctuations in temperature, pressure or turbulence can be compensated for electronically by reflecting sound off a target located at a known distance. Noise, such as that associated with the passing of a train, may be detected by the sensors. This could potentially cause inaccurate measurements to be made. If such a problem were to exist, the sensor would not be effective during times of high background noise.

An ultrasonic sensor cannot monitor all points along a prescribed length of guideway as is possible with other sensors, such as acoustic emission sensors. Measurements taken with an ultrasonic transducer are related to changes in sound propagation time over a fixed path. The number of sensors necessary to monitor a section of guideway would depend upon the spacing between sensors that would assure adequate knowledge of the structure.

Additionally, an acoustic sensor cannot monitor guideway conditions "continuously". The sensor operates by transmitting one burst of ultrasonic energy. This energy or wavefront, must reflect off the surface of interest and be detected by the same sensor or a different one located at another location. The sensor cannot transmit another wavefront until enough time has passed to detect the previous one and any echoes have died away. Therefore the rate at which ultrasound is transmitted is directly dependant upon the total round-trip distance that the wavefront must travel. For example, an air coupled transducer 1 meter from the guideway surface can transmit ultrasonic energy at a repetition rate of approximately 150 Hz. If the sensor is moved closer the maximum allowable repetition rate will increase. It is likely that most Maglev applications will permit rates from 100 to 1000 measurements per second. This would allow measurement of the amplitude of low frequency vibrations, but not high frequency vibrations.

3.4 Environmental Sensitivities

Temperature:

All measurements made using an acoustic transducer will be based upon the amount of time required for sound to travel to a reflector and return. This time-of-flight measurement can be influenced by either a change in the total distance that the sound must travel, or by a variation in the velocity of sound in the medium of propagation. Although temperature effects are minimal for solids such as steel, significant variations can occur in air. For normal temperatures, the velocity increases about 1% per 5.5°C (10°F) increase in temperature. If this change in velocity is not compensated for, then it may appear that the reflector had moved even though it had remained stationary. Air coupled ultrasonic systems typically have methods by which to correct for temperature fluctuations. The most common method is for a small stationary reflector to be placed at a known distance away from the monitoring transducer or a separate transducer. The arrival time of the reflected ultrasound is monitored electronically and corrections made accordingly. Temperature sensors can also be used for a more direct method of arrival time correction. Temperature compensation would be necessary for any maglev application due to exposure to environmental conditions.

Atmospheric Pressure:

Normal fluctuations in the atmospheric pressure will not have a significant effect on the accuracy of an air coupled ultrasonic system. However if pressure conditions approach that of a vacuum then the system will become ineffective. Although regions of low pressure will exist near a maglev train traveling at high velocities it is anticipated that the magnitude of this pressure drop will not significantly affect sensor measurements.

Acoustic Interference:

Noise generated by events external to the ultrasonic system can be detected by the system. In order for this to occur, the background noise must have frequency components that are within the bandwidth of the transducer. If noise is detected with the sensor then erroneous, unreliable measurements will be produced. It is expected that acoustic interference will be a significant problem during the passing of a Maglev vehicle at high speeds. Past studies have shown air passing through orifices or around geometrical obstructions at high velocities can create sound with harmonics well into the ultrasonic frequency range. It can be expected that similar sounds will be generated by a Maglev vehicle traveling at speeds where vehicle noise is significant. Although attempts could be made to position baffles in close proximity to the sensor in order to reduce unwanted noise, the most promising method for reducing this problem would be to use an averaging routine. It may be necessary for any data taken during the passing of a vehicle to be ignored.

Moisture/Humidity:

The majority of air coupled transducers will not operate properly if liquid is splashed or condensed on the transducer face. However one vendor that has been contacted is introducing a transducer that can be operated in typical environmental conditions (rain, snow, temperature variations). Additionally, humidity can affect the absorption of sound by air. These effects can be overcome, but must be considered in any final design. Finally, humidity affects the velocity of sound. This may be corrected by the methods used for temperature correction.

Air Motion:

The movement of air between the transducer and the reflector can cause inaccuracies in the distance measurement. This is caused by the addition of the air velocity vector to the sound velocity vector to give the net propagation vector.

A steady side wind produces an effect like crossing a river in a boat; the heading is different, the effective velocity is slower and, with a strong enough wind or long enough path, the sound may never get back. As an example: a side wind of 17m/sec (37 mph), 1/20 the speed of sound, will cause a deviation of nearly 3 degrees in the direction of the propagation vector. This will cause an increase of 0.125% in the propagation time for the sound. At a working distance of 1 meter, this would appear as a distance change of 1.25 mm. Also, most detector systems use a threshold for detection of the returned sound, and the change of the propagation direction will cause a loss of signal amplitude, resulting in the threshold being crossed later in the risetime of the waveform. If the operating frequency is 100 KHz and the phase delay caused by low signal amplitude is 90 degrees, this will produce another 0.75 mm in distance error, for a total

2 mm error. The deflection angle is linear with wind velocity, and the apparent distance change is quadratic.

A steady wind along the direction of sound propagation can have an even larger effect. For the same velocity, 5% the speed of sound, the round trip time is increased 0.5%, or apparently 5 mm at a 1 meter working distance. This effect is quadratic with wind velocity.

In either of these cases, the flow would likely be turbulent, causing further random fluctuations in the propagation vector.

Air turbulence can be difficult to compensate for if it isn't consistent throughout the sound path. The best method would be that used for temperature compensation, a reference which will be affected the same way. Obvious precautions can be taken to minimize this potential problem. Barriers could be placed around the volume through which the sound is to travel as a means to inhibit air movement. Care would be needed to design these barriers to avoid dust and snow collection. Waveguides that blow a continuous stream of air are another method, but likely to cause problems themselves.

Like acoustic interference, air turbulence effects will become most significant during the time the Maglev vehicle is traveling in close proximity to the sensor location. It is probable that the air turbulence created by the moving vehicle will degrade the accuracy of any measurements made during that period. It may prove necessary to ignore data from this sensor system during the passing of a high speed vehicle. If so, the system would have a hard time detecting vehicle induced vibrations or displacements.

Magnetic Fields:

Air coupled ultrasonic transducers can be selected so that operation in close proximity to the guideway can be avoided. It is anticipated that this flexibility in sensor position can be used to alleviate any adverse effects that strong magnetic fields may have on capacitor type transducers.

The structural coupled transducers must be attached directly to the Maglev guideway, exposing the sensors to strong magnetic fields. The experiment found in Appendix A3 indicated that strong magnetic fields do have an effect on piezoelectric type transducers by slightly increasing the natural frequency of the crystal as well as damping it. Although the effects measured in this experiment did not seriously hamper the ability of these sensors to operate effectively, the effects caused by intense fields such as those produced by a Maglev propulsion system are still not known.

3.5 Reliability

The reliability of an air coupled ultrasonic system can be quite good. There are no moving parts to maintain and the electronic circuitry can be protected from environmental effects. The component in the system with the highest probability for failure would be the transducers. Although both piezoelectric and electrostatic transducers have proven to be very durable devices it is anticipated that a Maglev system would require sensors to be subjected to harsh environmental conditions. This could limit the life spans of these components even though environmentally hardened sensors are available. It is anticipated that the average life span of such a sensor could be 3 to 5 years.

3.6 Costs

The cost of commercially available ultrasonic sensors ranges from approximately $250 - $350 per sensor in small quantities. It is anticipated that three sensors would be placed at each guideway expansion joint; one sensor would measure lateral displacements, one for vertical displacement, and one for gap measurements. In addition, every kilometer or so there would be another sensor or two used in detecting and measuring ice and snow build up. Each sensor group would require a small programmable controller which would analyze data and be responsible for data communication. These clusters of sensors and their controller would probably cost under $1500. If a sensor group was placed every 20 meters, then the total costs for the ultrasonic sensors would be approximately $75,000/km. The estimate does not include communication cables (probably fiber optic) and main system computer..

3.7 Data Handling

There are two basic types of commercially available air coupled sensors that are distinguishable by the type of output produced. Linear or switched output transducers are commonly available. Linear output devices provide a voltage or current variation that is linearly related to the amount of time required for the reflected signal to be detected after being transmitted. The distance can be directly calculated using this time measurement if the velocity is known. The range (minimum & maximum arrival time) and sensitivity of the output is adjustable for each sensor. A switched transducer provides a predetermined voltage or current depending upon whether a reflector is located in or exceeds the limits of an established distance window. A switched transducer cannot be used if distance measurements are to be made.

In either case, the measurements would be read by a local computer which would monitor the systems and pass results on to a central computer. The local data processing requirements would be minimal.

3.8 Redundancy of Coverage

The ultrasonic sensors will be located at various sites along the guideway. At each monitor location multiple sensors will be used for condition monitoring. It is anticipated that a group of three sensors will be adequate for guideway monitoring at a given location. The actual number of sensor groups necessary to sufficiently monitor a given length of guideway is largely dependant upon the design of the structure and the type of section being monitored (curves or switches versus straight sections). However it would seem plausible that a sensor group located at each guideway expansion joint would provide adequate coverage. Each sensor group location would consist of three separate transducers; one each to measure lateral displacements, vertical displacements, and axial displacements (expansion gap). Periodically there might be a fourth sensor for ice build up, measured through a metal plate, or a fifth for ice and snow measurement through the air. These measurements are related only to the discrete point where the sound is being reflected. Although the ultrasonic sensors cannot determine the exact state of the guideway between sensor group locations, if significant movement is present in a guideway section then some displacement (lateral and/or axial) will be detected at the end of that section. Axial displacements either due to mechanical failure or thermal expansion will be detected by gap measurements at both ends of the section. The transducers for detecting and measuring ice build up will not be needed at every sensor group location. It may be adequate to space these sensors at significantly larger distances as determined by local weather patterns. In regions without localized storms, these sensors could be miles apart.

4.0 Microwave Sensors

Microwave sensor systems may be separated into two classes. One class is radar, in which pulses are sent out and the time to a return signal is measured. This type of unit is not useful for monitoring guideway vibration and displacement because the distances to be measured correspond to picosecond timing, which is too fast for inexpensive electronics currently available. The second class of device operates by sensing changes in the near field, within a few wavelengths of the antenna. These devices may be useful.

4.1 Physical Processes

Microwave sensors operate in a specific part of the electromagnetic spectrum. Thus they are part of a range of possible devices for the use of electromagnetic effects to detect changes in the condition of the guideway.

All electromagnetic sensors operate by sensing the conductivity, permeability, and dielectric constants of their surroundings. That is, they can be viewed as systems which produce fields which interact with their surroundings. Any changes in those interactions then produce changes in the fields which are detected by the circuitry. For guideway applications, these changes in the electromagnetic characteristics of the environment will be caused by relative motions of the sensor and the guideway structure. The movements may be very slow, as gradual degradation of the structure, or rapid, if an earthquake or airplane knocks a section down, or the motions may be vibrations from wind or vehicle passage.

Electromagnetic devices which use static or low frequency fields for interaction with their surroundings are subject to drift, and hence are not desirable for monitoring small changes over long times. In particular, instruments which rely on magnetic measurements are likely to be affected by the repeated passage of Maglev vehicles. Higher frequency RF devices have better stability, but their long wavelengths require the detection of very small fractional changes in response. The best possibilities for electromagnetic monitoring of the guideway come from devices operating at wavelengths comparable to the distances involved. A guideway condition sensor should be capable of detecting millimeter displacements in alignment of guideway sections. At a frequency of 10 GHz, the radiation has a wavelength of 3 cm. This appears to be the right order of magnitude for monitoring by electromagnetic effects.

A commercially available example of such a sensor is called a microwave displacement detector, which is basically a microwave interferometer operating at a frequency of 10.525 GHz and a wavelength of 2.85 cm (1.12 inches). The sensing head is a small disk-like antenna placed at the end of a flexible coaxial cable. The antenna radiates a low intensity microwave signal and is placed 1 to 2 cm (approximately 0.5 inch) from the target. A portion of the transmitted signal is reflected by the target back into the antenna. This reflected signal is separated from the transmitted signal within the instrument. Then it is fed to a phase comparator that produces an output voltage proportional to the phase difference between the transmitted and reflected microwave signals. Any change in distance between the target and the antenna produces a phase change which alters the voltage produced by the phase comparator. These voltages can be converted directly into displacements.

4.2 Capabilities

The commercially available microwave displacement detector described above can provide a non-contact measurement of displacement and vibration. Alignment and position between the target and sensing head are not critical. The device contains two microwave signal generators that are phase locked together with a frequency separation of 1 Mhz. The two generators are used so that the actual phase comparison can be made at the 1 Mhz difference frequency rather than at a microwave frequency. This allows the use of a phase comparator able to produce an output voltage that is linearly related to phase difference and independent of the amount of signal reflected by the target. The same linear output is obtained from targets having either high or low reflectivity. Therefore, target composition is not a major consideration, since all materials whether they are metal, plastic, rubber, wood, or glass reflect sufficient microwave energy to permit accurate measurements.

The linear analog range of the instrument is half a wavelength, approximately 1.4 cm. The sensitivity is approximately 12 microns at full bandwidth of 5 Khz. This sensitivity is probably better than necessary, and the working distance too short, for many Maglev applications. However, it might be useful for monitoring the extent of mid-span flexure from measurements at the end of the span. The system will measure the distance from the antenna to an object, so a mounting separate from the object is required. This could be a separate structure, but most likely a mounting on one part of the guideway would be used to monitor the distance to another part of the guideway. The requirement of mounting the sensor on one structural member to observe motions of another member means relative motions will probably be very small, because the flexure will cause rotations around a pivot point very close to the sensor.

It is likely that similar performance could be designed into other instruments tailored for particular guideway applications. The same or very similar circuitry could probably measure 1 mm over a 15 cm range at 1 Ghz. Such lower frequency, longer range systems could be ground mounted to observe midspan motions or switching operations.

4.3 Limitations

Microwave sensors for monitoring the physical condition of a guideway should probably be integrated into a system for continuously monitoring the entire guideway status, such as a radar imaging system which could detect obstructions, intrusions, weather conditions, and vehicle position and speed. However, this report is specifically limited to sensors for monitoring guideway physical condition and structural integrity.

The main limitations for the microwave displacement detector are the necessity for close proximity of its antenna to the guideway, and the fact that it does not provide continuous monitoring of the entire guideway, but only spot checks at strategic locations along the route. These could be located at or between joints to provide data on guideway integrity and condition, on the assumption that the joints are more likely trouble spots than mid-span.

4.4 Environmental Sensitivities

The microwave circuitry will need protection from the natural elements to insure accurate measurements. The antenna should be unaffected by moisture and heat. If placed properly so that the guideway provided some shielding, it could be protected from most foreign materials. The electromagnetic fields from the passing Maglev vehicle should not harm the effectiveness of the sensors, assuming the circuits are shielded from transient induced currents.

The microwave circuits have a long lifetime expectancy, and in many applications they run continuously 24 hours a day. Temperatures from -30° to 50°C have no adverse effect on the units. Humidity tolerance was described as excellent and should not be of concern. It was suggested that a water-tight NEMA box be used to house the unit. In general, microwave systems are designed to work outdoors in all weather. The various military and communications applications have solved the environmental problems.

4.5 Reliability

Manufacturer's technical personnel maintain that their products have provided long and continuous services without any mechanical failures in numerous applications. Regularly scheduled system inspections would provide the reassurance necessary for a monitoring system responsible for the safety and integrity of a transportation system as fast as Maglev.

4.6 Costs

The initial cost for the microwave displacement detector providing the capabilities as described above in Section 4.2 are approximately $22k for each unit purchased. Lower priced units ($12K) might become available, although they would possess slightly lower capabilities. These are unit costs using presently available equipment. Allowing for volume purchases, and the fact that single chip microwave transceivers are under development, the costs should be in the range of $2-5k per installation. The guideway method of construction and/or number of joints along the route will help determine the number of microwave monitoring units to be located along the structure.

4.7 Data Handling

The data handling requirements of this system, like the others, depends largely on what it is called upon to do. There are no special requirements beyond the general summary discussion (section 6.3).

4.8 Redundancy of Coverage

The microwave displacement detectors, if placed at strategic intervals along the guideway, would not offer redundant coverage from one unit to the next since they would likely be too far apart. It would not be cost effective to have enough of these devices to provide redundancy in the event of sensor failure. They would, however, provide excellent detection capabilities for misalignment of guideway sections and vibration of the guideway, as well as some degree of overlapping coverage for other sensor types in the same area. For interaction with other systems, see the summary discussion.

5.0 Fiber Optic Sensors

Fiber optic systems share one important advantage with acoustic emission monitoring systems, over the other possible sensor systems. All energy propagation, interaction, and detection occur within solid materials. There can be complete immunity to the effects of rain, snow, fog, and dust.

5.1 Physical Processes

In recent years fiber optic systems have undergone extensive development for both communications and sensing systems. It is routine to send light pulses through fibers for many kilometers with very little loss of intensity, in communications systems. In sensing systems, fiber optic sensors are used for intrusion detection, stress and strain detectors in aerospace composites, and hot spot detectors. In these, an optical fiber is embedded in or bonded to the structure to be monitored. Stresses and strains are mechanically coupled to the fiber, and these stresses and strains modulate the transmission of light through the fiber.

The fiber is a waveguide for the light. Anything which produces a change in the optical properties (dimensions and index of refraction) will cause a change in the light propagation. Possible changes which can be detected include intensity, polarization, and phase. Light intensity modulation is preferred because it gives potentially large dynamic range and is compatible with single ended excitation and readout. Single ended operation is desirable because it reduces the length of fiber needed and, more importantly, allows measuring the distance to a perturbation to a resolution of 2 cm over a distance of 10 km.

The instrument used to obtain this performance is an optical time domain reflectometer (OTDR). These instruments are commercially available and are routinely used to detect and locate breaks in fiber optic cables.

For use with an OTDR, the sensor fibers would be bonded to or embedded in the structure. They could be used to continuously monitor the entire structure, or only selected critical points. The trade-off is discussed under capabilities and limitations. In either case, the sensing fiber could consist of a metal or polyimide buffered glass-on-glass optical fiber enhanced for microbending loss. The fiber could be a commercial type with 62.5 micrometer (0.0025") core and 125 micrometer (0.005") clad diameters.

Small spatial deformations of the fiber are called microbends, and these microbends induce light intensity loss in optical fibers via modal conversion and light loss through the cladding. In other words, by squeezing or bending a fiber, light can be removed from it. Of particular importance to OTDR functioning, some of the loss is by scattering back toward the source. It is this reflected light which is detected by the OTDR, with time giving distance and amplitude giving the magnitude of the stress.

Changes is fiber mechanical deformation amplitudes as small as $4x10^{-10}$ meters are easily detected. Induced microbending enhances fiber sensitivity to mechanical perturbation and microbends can be purposely induced in several ways. For example, special thin walled sleeves with a corrugated ID may be pressed onto the fiber along its length, or suitable fiber buffer coatings may be used to prestress the fiber. Typical buffer coating thickness is 10 to 20 micrometers. Such microbend enhanced fibers are available for security surveillance monitoring.

In a typical installation for point measurements, the fiber has several microbends with a period of 1.5 mm. The fiber is attached to the structure at two points 5 mm apart. Strains in the structure produce changes in the fiber length, which changes the spatial period of the fiber, changing the attenuation. As an alternative, the fiber can be mounted so that strains in the structure cause compression or tension in the fiber. This changes the amplitude of the microbends, changing the attenuation. In general, fiber optic strain gauges can be used much like conventional strain gauges with the added abilities to place many gauges in series and provide immunity from electric and magnetic field effects.

Alternatives to intensity modulated distributed sensors are wavelength modulated sensors. Both Fabrey-Perot and grating sensors have been demonstrated in the laboratory. However, very complex signal processing is needed to extract information from up to 10 multiplexed wavelength sensors along a single fiber. The temperature sensitivity of these sensors is also a concern. Nevertheless, over the next several years, development of wavelength modulated sensors for aerospace applications may solve these problems and result in systems of interest to Maglev.

5.2 Capabilities

The distributed fiber optic intensity sensor has the capability to provide contact measurement of stress and strain of the guideway on a totally continuous basis. The system's OTDR could display, on a CRT, the light intensity vs. distance along the fiber length, or output the information to a data acquisition system for analysis. Fiber optic sensors could possibly be installed across guideway joints or expansion joints (depending on the guideway configuration) to detect displacement or misalignment between sections. When connected to a central computer communications network, input from all the OTDRs could be monitored at one location. In addition, if significant damage occurred to the guideway with enough force to actually break the optical fiber, the OTDR could exactly determine where the break is located simply by analyzing the light return time from the break.

The number of sensors per fiber is set by the dynamic range of the OTDR and the loss per sensor. If the OTDR has a dynamic range of 32 Db, and each sensor has a normal static loss of 0.3 Db, then about 100 sensors can be used on a single fiber. If the sensors are far apart, they could be connected by means of low loss communications fiber, with interconnection losses of 0.1 Db per splice, or 0.01dB per splice if fused splices are used. At one sensor per 20 meters, a sensor string would be about 2 km long. To monitor a distance of 100 km from the OTDR, 50 communications fibers could be multiplexed, each attached to its 2 km sensor string. Hundreds of fibers can be multiplexed on a single OTDR, many more than would be needed, as shown in the section on costs.

5.3 Limitations

One limitation of the fiber optic sensor method concerns the attachment of the optical fiber to the guideway sections. Examination of the differential thermal expansion between steel (rails) and fused silica shows that the optical fiber will experience a 0.1% elongation over the temperature range -30° to 70°C. This is well below the 3% maximum elongation recommended to remain below the fiber break load; however, a bonding material able to sustain the same 0.1% elongation is required.

The microbend sensor detects changes in the pre-existing microbend. This makes it essentially a point sensor. For measuring strains over a joint, a mechanical means would have to be used to apply a known fraction of the total strain to the microbend region. This is quite feasible, but some development would be needed for the particular geometry and expected deflections of each application.

5.4 Environmental Sensitivities

The microbend sensors would be protected by the guideway structure, whether bonded or embedded. Some packaging of the connecting cables may be necessary to protect them from the elements. The OTDRs would require a protective covering to insure accuracy of the instrumentation. The optical fibers and connecting cables should be immune to the electromagnetic fields from the vehicle. Temperature and humidity variations should have no adverse effect on the fiber optic system.

5.5 Reliability

The reliability of the fiber optic sensor in this application remains to be determined as no previous examples of a monitoring system of this magnitude have been found. However, as the system would be monitoring for a change in an otherwise static situation, and has no alignment considerations, and the sensors have no active components, reliability should be high. The most suspect part in the system would be the active electronics of the OTDR and multiplexer. Reliability of such electronics is good and improving rapidly. This question should be resolved at the time a decision is being made on the application of the system to an actual design.

5.6 Costs

A fiber optical sensor system would consist of segments of fiber with about 100 sensors each. An array of these sensor segments would be multiplexed into an OTDR. Enough of these OTDR arrays would be used to monitor the needed length of guideway. The question of cost of the system depends on the costs of the components and the number and length of the segments attached to each OTDR. These costs can be estimated for any particular system at current prices, but the first requirement is the establishment of a means of determining the lowest cost system to monitor a given sensor layout. That is, we need a means of deciding on the number of OTDRs to use, and how many fiber segments to place in each array. The following description gives a way to determine the lowest cost system based on prices at the time the decision must be made.

Assume the sensor locations have been selected, and the number of sensors per fiber is fixed. This fixes the length of each segment and the cost per unit length of the sensor layout. How many OTDRs should be used? The OTDRs are expensive, maybe $20k each, and the fibers that connect the segments to the OTDR are $0.80 per meter. If 1000 fibers are multiplexed to each OTDR, the fiber cost near the OTDR is $800 per meter, so significant savings can result from using more OTDRs with fewer fibers each.

First, we find the cost of connecting one OTDR array. The array has **n** segments, and each segment has length **L**, giving an array length of **nL**. If the OTDR were at one end of the array, it would require **n** fibers of average length **nL/2** each. We can minimize the fiber length by placing the OTDR at the center of the array, using **n** fibers of average length **nL/4**. The cost

C of the array connections is the cost **E** of the OTDR and its multiplexer, plus the cost **c** per meter of fiber times **n** fibers times the average length **nL/4**, or

$$C = E + cn^2L/4.$$

The cost per unit length is

$$C/nL = E/nL + cn/4.$$

The minimum cost per unit length occurs when the derivative of **C/nL** with respect to **n** is equal to zero, or

$$d(C/nL)/dn = -E/n^2L + c/4 = 0,$$

$$E/n^2L = c/4.$$

This lowest cost relation is then used to find the best number **n** of segments per array.

$$n = (4E/cL)^{1/2}$$

As an example, for a high measurement density system, we might have a segment consist of 100 sensors at 10 cm spacing, so **L** = 10 m. If **E** = $20,000 and **c** = $0.80,

$$n = [(4 \times 20000) / (0.8 \times 10)]^{1/2} = 100.$$

This gives **nL** = 1000 m, or one OTDR per kilometer.

For a lower density system, there might be a cluster of 10 sensors at each joint, located 20 m apart. At 100 sensors per segment, there will be 10 clusters over a distance of 200 meters. This gives L = 200 m, n = 22, and nL = 4.4 km.

A rearrangement of the minimum cost relation gives

$$E = cn^2L/4$$

which we see, from the array cost equation, means the minimum cost occurs when the cost of the OTDR-multiplexer installation is equal to the cost of the connecting fibers. To this cost must be added the cost of the sensor layout; sensor costs, intersensor cables, connection, and installation; and also the cost of a system to collect data from all the OTDRs and feed it to a central control point.

Maintenance costs for the fiber optic sensor system should be negligible. Any damage to the optical fiber should be a result of damage to the guideway.

5.7 DATA HANDLING

The data handling requirements for this system are not significantly different from any of the others, as it is assumed that a local computer would act as a data analyzer and concentrator to communicate with the central controller.

5.8 Redundancy of Coverage

The fiber optic intensity sensor, if placed in a high concentration arrangement (1 sensor/meter or so), should allow the monitoring of multiple data points for a given area of guideway. Should a disruption occur, many sensors in the area should detect the problem. If the sensors were configured in a less dense arrangement (1 sensor/10m), it is possible that localized moderate damage to the guideway could go undetected by the system. It is likely that a second sensor system (AE, UT, etc.) would have to detect such damage. However, for the costs involved, the less dense arrangement would provide a very representative sampling of the overall condition of the guideway.

If the fiber optic sensor system mentioned above were to fail completely, then all of the other four sensor types except AE could detect misalignment.

6.0 Summary

This report considers various means of monitoring guideway condition. They are acoustic emission monitoring, ultrasonics, fiber optics, infrared, and microwave. The following sections compare these sensor technologies under various criteria, giving capabilities and limitations of each.

Acoustic emission monitoring detects sound given off within a structure. If a structure contains growing cracks, they will emit sounds. Sounds will also be generated by structural parts rubbing together. The various causes of structural sounds are generally distinguished by the increase in noise with increasing damage. The sounds of cracking arrive in sharp bursts. By measuring the noise burst's time of arrival at different locations, it is possible to locate the source of acoustic emissions. By proper selection of operating frequencies and sensor spacing, this system is capable of monitoring the entire guideway for growing damage.

Ultrasonic monitoring also uses sound waves, but they are generated as part of the testing process. Much of the work in ultrasonic testing involves propagation of sound through solid materials. Such "traditional" ultrasonic testing will probably be useful in evaluating the condition of a guideway, such as in the evaluation of acoustic emission sources, but it is unlikely to be useful for continuous monitoring except for the detection of ice accumulations. However, the use of airborne ultrasonic waves is more promising. Airborne ultrasonics can detect displacements between sections of guideway and measure vibration frequencies and amplitudes.

Fiber optic systems are capable of monitoring the entire guideway for sudden failure. If a fiber is broken, the location of the break can be detected instantly with very high accuracy. The fibers can also contain localized strain sensors, for monitoring potential trouble spots such as joints.

Inexpensive infrared or visible light systems can be used for monitoring relative positioning of components of the guideway. More elaborate systems are capable of monitoring vibrations and displacements at long distances.

Microwave systems can be used to monitor positions and vibrations of components. They are also potentially useful for monitoring intrusions and obstructions on the guideway, but such applications are outside the scope of this report.

6.1 Physical Processes and Available Equipment

The possible sensor systems involve energy propagation, either as sound or electromagnetic radiation. The electromagnetic methods are subdivided by whether field amplitude or energy transport is the basis of detection.

The methods are also distinguished by whether the energy is transmitted through the air or through a solid structure.

Acoustic emission monitoring uses piezoelectric devices to detect structure-borne sound, generally in the range of 100kHz to several MHz. The higher frequencies do not travel as far as the lower frequencies. This is caused by scattering attenuation, which increases with the square of the frequency, and by mode conversion effects. Sound propagates through a structure in a mixture of longitudinal, shear, surface, plate, and other modes. Each mode has its own velocity, and boundary interactions assure that energy is continuously coupled between the modes, stretching the pulse in time and preferentially attenuating the shorter wavelengths. On the other hand, lower frequencies give poorer source location and are more likely to be masked by environmental noises. Based on experiments on steel rails (see appendix A4), it is likely that broad-band acoustic emission sensors every 100 feet with a center frequency of 250 kHz would give good coverage. The important noise events, that indicate cracking or movement of the guideway, would occur when the vehicle is passing and applying load to the structure.

Ultrasonic sensors, for use in air, are restricted to frequencies of 1 MHz or lower because of attenuation in air. The path length and electronics used determine the useful maximum frequency within this limit. The transducers are pulsed, and the time to an echo gives the path length. Sub-millimeter distance resolution is easily achievable. Transducers may be piezoelectric or electrostatic. Beam directivity is determined by the ratio of transducer diameter to wavelength. Highly directional beams are possible, which minimizes unwanted echoes but also tightens alignment requirements. Displacement sensors can have much larger ranges than needed, but vibration frequency bandwidth is limited by the rate at which pulses can be transmitted. Repetition rate is limited by the need for echoes from each pulse to die out before the next pulse is sent.

Fiber optic cables are available with extremely low loss, allowing the use of fibers many km long. These are single mode fibers, which avoid the losses associated with mode conversions. In operation, a pulse of light is sent down the fiber and either the transmitted or reflected pulse is observed. For Maglev applications, the reflected pulse is most likely to be useful because it allows single ended operation with timing to provide location. If a fiber is broken, the time to the reflection from the break gives the distance. This can be measured to much greater accuracy than necessary for this application. Fiber optic strain gauges operate by distortion of the fiber producing a partial reflection of the light passing through. This reflected light is detected and its power measured to determine the strain. A single fiber can have as many as 100 strain measuring sections, limited by the passive losses of each section. The location of each strain gauge section is determined from the pulse return time.

Infrared and visible light sensors can monitor displacement and vibration by as simple a means as a light source, a target reflector, and a diode detector. They can also be as complex as TV cameras or interferometers. The number of possibilities for systems which use light propagating through the air is greater than for any of the others considered in this report. Unfortunately, optical systems are very sensitive to dust, fog, and snow. For this reason, optical systems are best used as inspiration for similar systems using other forms of energy propagation.

Microwave systems can be used for some of the applications of optical systems, but their much longer wavelength minimizes weather effects. The much lower photon energy also eliminates the use of photodiodes. Microwave systems are based on electronics fast enough to follow the electromagnetic fields. For a displacement and vibration sensor, a microwave system could monitor the phase difference between a transmitted signal and the reflected return signal. The bandwidth capabilities are much greater than available with ultrasonic systems, but the useful distance range is determined by the wavelength. Transmission of a pulse and timing the return are not as easy as with ultrasonics because of the factor of one million difference in propagation velocity. It is also not as easy as with fiber optics because of the difference in the electronics used.

For all the systems considered, the equipment capabilities are set by the transducer capabilities as described above. The actual hardware used will probably be designed for the application, rather than standard units now available.

6.2 Environmental Sensitivity

All the systems considered include electronic components, which must be protected from the environment. This can be done for everything except temperature, and military specification electronics should handle most temperatures encountered. Protection against moisture and corrosion is the major consideration, and this is routinely handled for communications systems. The unique difficulty in this application is the possible presence of intense magnetic fields. The fields themselves shouldn't bother any of the electronics, but the eddy currents caused by the rapid change in field intensity as a vehicle passes could damage the circuits. It will be necessary to consider location or shielding or special design for the electronics packages.

The acoustic emission and fiber optic systems can be completely protected from the environment, but ultrasonic, infrared, and microwave systems must transmit energy to and from the environment. They will need to have their transducers protected.

The problems of keeping optics clean, and the problems of snow and fog, will probably eliminate most infrared applications. Microwave transceivers can operate behind sealed surfaces which are transparent to the radiation, and precipitation is much less of a problem. Ultrasonic transducers need to have the transducer face exposed, and they will be subject to mechanical damage. All three systems will have to be installed so that they do not make good nesting or roosting sites.

Some wildlife are able to hear ultrasound. Low repetition rate short bursts are probably not a problem, but this should be checked by prototype before a full system is built. The FCC will have something to say about microwave systems.

6.3 Reliability, Data Processing, and Costs

Most modern electronics circuits are highly reliable, but in order for the system to be reliable all the sensor systems must be able to detect the failure of any sensor or its electronics. Such failure would be reported with any other normal or abnormal readings to the central control system. Given the probably difficult electrical environment, reporting to the central control system should probably be via fiber optic communications.

None of the systems have great differences in data processing costs, since no individual sensor needs more processing than a low cost microprocessor can provide. The differences lie in the costs of the electronics packages. The electronics packages are difficult to estimate, as the desired functions will have a large impact on the needed electronics. For all the systems considered, given that quantities used will be very large, it should be possible to build single board enclosures at much lower cost than present laboratory quality low volume units. In addition to other costs, all systems need electric power supply, installation, and reporting capability to a central control system. The means of reporting to central control, and whether individual packages report back or summaries are generated by local processors, will depend on system considerations at the time of system design.

Conclusion

At present, it appears that the most useable applications are acoustic emission monitoring for slow crack growth, fiber optics for catastrophic failure and displacement between sections, and ultrasonics or microwave for vibrations and alignment of sections. Ultrasonics can also be used for detection and measurement of snow and ice accumulation.

Appendix #A1 - Ultrasonic Detection and Measurement of Ice Buildup

Introduction / Goals:

Due to the nature of the levitation and propulsion systems being considered for the Maglev system, the build-up of ice on the guideways resulting from freezing rain or sleet could adversely affect the performance of the vehicle. This experiment will assist in determining the feasibility of a monitoring technique with the potential to quickly detect ice formations on exposed guideway surfaces and to provide data related to the thickness of the ice layer. There were no assumptions made concerning a "safe" amount of ice which may be traversed by a maglev vehicle. Those ice thickness safety parameters will have to be determined once vehicle and guideway specifications have been finalized. However, there was an assumption made concerning the maximum amount of ice to be examined at this time.

Experiment #A1 was performed under laboratory conditions to prove the feasibility of using standard ultrasonic transducers to detect the presence of ice and provide thickness measurements. This experiment examined the possibility of measuring ice build up by propagating sound waves through the guideway structure. There were no assumptions made as to the shape of the guideway. The experiment was designed simply to propagate sound through various metal-path thicknesses and typical ice-path thicknesses to examine the penetration/resolution performance of this approach.

Background / Method:

It was hypothesized that ice build up can be measured by propagating sound waves through the ice layer. In order to successfully introduce sound waves into the ice material a transducer must be directly coupled to the surface of structure to which the ice has formed. Therefore for a direct coupling method to work the sound must propagate through the guideway structure, through the guideway/ice interface, reflect off the outer surface of the ice and return to the transducer. The thickness of the ice is determined by measuring the time-of-flight of the reflected signal.

Different materials possess different acoustic impedances, the magnitudes of which are determined by the product of the sound velocity and density for each material. An acoustic impedance mismatch often occurs. Consider the case of steel and ice. The velocity of a longitudinal sound wave in ice is roughly 68% that of steel. The densities of the two materials are also quite different. These factors produce an acoustic impedance mismatch sufficient to allow approximately 15% of the incident wave sound pressure to transmit through the interface. The remaining 85% is reflected back into the steel never entering the ice medium. Although very little energy is lost at the ice/air interface due to an almost total reflection, only approximately 15% of the remaining sound pressure will transmit back through the ice/metal interface. Therefore approximately 98% of the original sound pressure will be lost due only to the acoustic impedance mismatch at the ice/metal interface alone. Although the transmission losses associated with this interface are considerable, ice thickness determination may still be possible. In order for a thickness measurement to be possible, sufficient energy must be able to travel through the metal/ice interface, reflect off the ice/air interface, and travel back through the metal/ice interface back to the transducer. The success of this experiment will depend upon the ability to receive the sound that is reflected off of the ice/air interface.

The crystalline structure and porosity of ice makes it extremely attenuative, meaning sound waves are scattered very quickly and lose their signal strength over shorter distances. In general, the lower the frequency of the sound the greater the penetration distance. However the use of lower frequencies will decrease the resolution of the test.

Convesely, higher frequencies offer better resolution but will not penetrate as far through the same materials.

The laboratory set-up for Experiment #A1 consisted of a metal plate rigged to hold water for the formation of the ice, various in-house transducers, and three ultrasonic testing instruments. These elements are described in detail below.

The metal plate had been "stepped" in four different thicknesses ranging from 5.1 mm (0.20") to 20.3 mm (0.80") as shown in Figure A1-1. This test fixture would allow for various ice-metal thickness combinations. This was an attempt to circumvent the annoyance of ice surface multiples being "masked" by the metal surface multiples. The rectangular stepped plate was fitted with plastic sidewalls which were held securely with double-stick tape. Ice was formed in the four different metal thickness areas as shown in Figure A1-2. The height of the plate was 25.4 mm (1.0"), and water levels in the plate were varied to allow monitoring of the metal sections with various ice levels up to about 15.2 mm (0.6"). As for the flat plates, the maximum depth of ice was limited to about 20.3 mm (0.8"). That figure was based on the assumption that normal accumulations from ice would not likely exceed that amount.

The transducers employed operated within the range of 1 to 10 MHz, suitable for the distances and thicknesses being examined at this time. Below this range resolution was poor and made highly accurate measurements impossible. Above this range penetration of the ice was difficult. All transducers were from 6.35 mm (1/4") to 25.4mm (1"in) diameter.

UT instruments used in the investigation consisted of an USIP-12 and an USD-10, both manufactured by Krautkramer-Branson. Accurate time-of-flight measurements were made using a Panametrics PR 5052 and a Tektronics 2236 oscilloscope.

Results:

The results of the investigation showed that the ultrasonic method could work well for measuring ice thickness. In particular, the higher frequency transducers were better suited for the conditions present in the lab set-up. A 10 MHz - 1/2" transducer was able to penetrate 0.78" of ice sitting atop one inch of steel, but required very high gain to produce an easily recognizable signal (one not mistaken for noise or another metal surface multiple). The high gain was needed due to the rather thick cross-section of ice and the attenuation accompanying it. The lower frequencies easily penetrated the same thickness, but as expected, there was some difficulty in resolving the indications accurately.

Sound path travel times were determined using the time delay overlap feature of the 2236 scope. The time was measured between multiple ice layer reflections. The thickness of the ice was calculated by using the following relationship:

$$\text{thickness} = vt/2$$

where,

v = longitudinal velocity (4.01 E6 mm/s)

t = time

With ice approximately 0.78" thick the signals from the 10 MHz transducer were repeatable to within +/- 0.03mm. An accuracy level of +/- 0.3mm was achievable using a 5 MHz transducer due to the lower frequency signals as well as the damping characteristics of the transducer used. One problem made evident in the investigation was that of having multiple metal surface echoes arriving in time among the indications from the ice surface reflections during thin metal/thick ice examinations. Due to the slower sound velocity of ice when compared to steel, metal path reflections could interfere with the ice multiples. For thick metal/thin ice examinations, the distinctions were much more evident with metal path multiples not interfering with the ice/air interface signal. Figure A1-3 shows the signal associated with a 23mm ice layer over a 25mm thick steel plate. Difficulty was encountered when the thickness of the metal was less than approximately 1.5:1 as is illustrated in Figure A1-3. When the thickness of the base metal is below this limit, the multiple reflections of the metal interfere with the ice multiples. In this example the ice/air interface signal arrives in time after the sound has simultaneously made two complete round trips through the thickness of the metal. It is anticipated that this will not be a problem in an actual Maglev application since the probable thickness of the guideway material will be sufficiently thick.

Conclusions / Recommendations:

The feasibility of using ultrasonic transducers to detect and measure ice build-up on a flat metal surface was proven in the preceding experiment. With properly selected transducer frequencies appropriate for a given guideway thickness and material, ice collecting on the guideways could be monitored on a continuous or time-lapsed basis. This technique could be used to simply detect ice build up or actually measure its thickness. Ice forming on the guideway would cause ice related signals to be detected with variations in the arrival time of these signals drawing the attention of computer monitoring equipment.

It is optimum to use the highest frequency transducer possible which will penetrate the guideway thickness. It is possible to achieve highly accurate measurements using this method. It is estimated that accuracies on the order of +/- 0.3 mm should be achievable for a maglev application. The actual parameters and resulting accuracies necessary to perform such an inspection is dependant upon the geometry and material used in the maglev guideway design. This experiment has proven the feasibility of the concept but would require testing using a realistic mockup of the guideway structure.

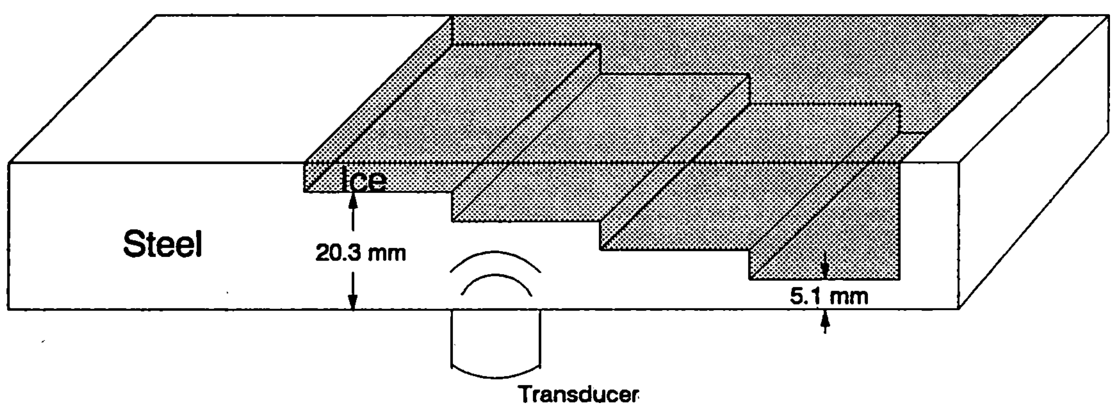


Figure A1-1: Cross-section of steel plate used in ice measurement tests.

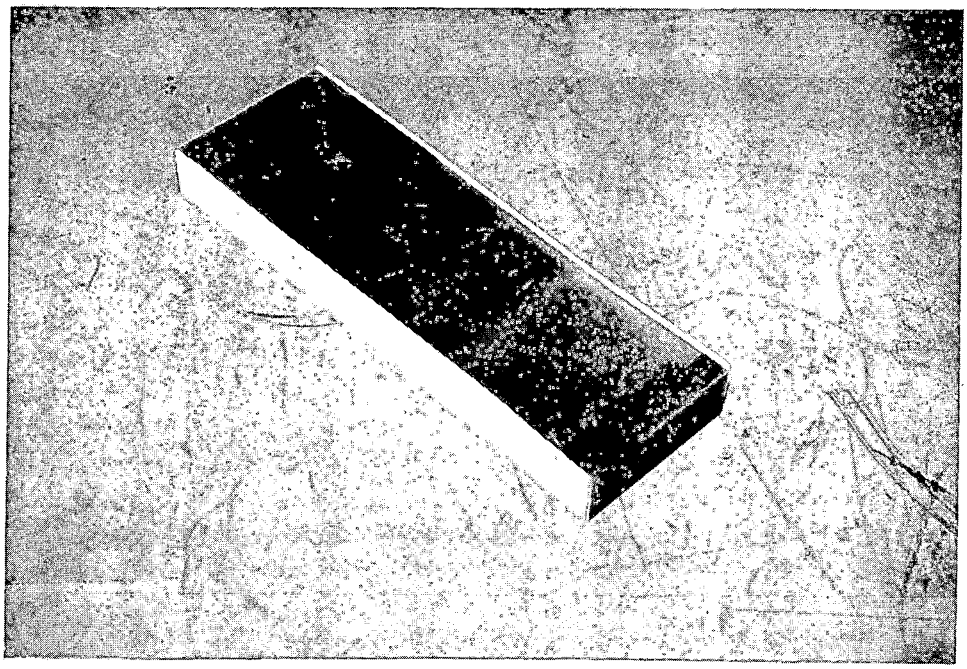


Figure A1-2: Test plate after the formation of ice.

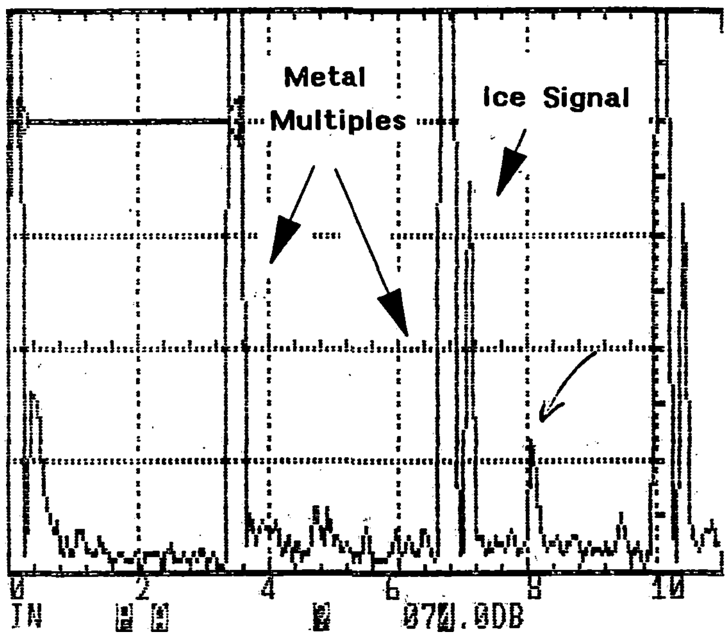


Figure A1-3: A-scan showing metal and ice multiples.

Appendix #A2 - Feasibility of Snow Detection using Air-Coupled Ultrasonics

Introduction / Goals:

The detection and measurement of ice buildup on guideway surfaces is a relatively straight forward measurement using air coupled ultrasonic transducers. Ice typically has a smooth surface and a high acoustical impedance which results in strong reflections. The amount of time required for the sound to reflect off the ice surface and return to a fixed traducer is directly related to the ice thickness. Unlike ice, snow provides an uneven surface and can vary in density resulting in a relatively low acoustic impedance. Therefore it is not clear whether snow will be detected by such a system due to the poor reflective properties. This experiment will investigate the ability of different materials to reflect ultrasound. The low density materials used in this experiment will provide information that will approximate the range of densities associated with snow. No natural snow was available for this investigation. The goal of this investigation was to determine whether air coupled ultrasonics will measure snow as well as ice build-up by testing low density materials.

Background / Method:

Figure #A2-1 illustrates the test setup used for this experiment. The transducer, pulser/receiver and ranging board where obtained from Polaroid Inc.. The transducer operated at a nominal frequency of approximately 50 kHz. A horn was made in order to confine the beam to a defined testing area. Without the horn the side lobes of the ultrasonic beam interacted with objects not related to the reflective material. An oscilloscope was used to monitor the reflected signal.

Four different materials were used as reflecting surfaces. Three of these materials were open celled foam rubber products with densities of .24 g/cm^3, .093 g/cm^3 and .032 g/cm^3.

The fourth material was polyester fiber commonly used as a filler for pillows etc.. This material had a very low density of approximately .006 g/cm^3. Obviously, the use of natural snow would have been preferable; however, it was not available at the time this test was performed. Typically, the density of snow is approximately 1/10th that of water or .1 g/cm^3. Therefore the materials selected for this test adequately encompassed the range of densities typical of snow.

Each sample was cut to 4"X 4" square and placeed in the sound beam at the same location and orientation. The amplitude of the signal reflected off each sample was then measured directly from the oscilloscope crt after being amplified 20 dB by a wide band amplifier.

Results:

Reflected signals were detected from all three of the foam rubber samples tested. The amplitudes of these signals ranged from 8V to 19V peak-to-peak. The following is a summary of these results.

Sample	Density (g/cm^3)	Amplitude (volts p-p)
LS-1519	.24	19
E-25SI	.032	10
EF-47	.093	8
Polyester	.0062	No Signal

In contrast no reflected signal could be detected when using the polyester sample. In addition, it was observed that reflections from a surface placed on the opposite side of the polyester sample could be detected. This indicated that the ultrasound was able to effectively penetrate through the material. An increase in the amplitude of this signal was observed when the polyester sample was removed. This result indicated that the material is attenuating the ultrasonic energy through scattering but is unable to reflect a coherent sound wave.

Conclusions / Recommendations:

This experiment indicated that materials with densities at or around that of snow can be detected using air coupled ultrasonics. The one sample tested that was not detected had a density that was approximately an order of magnitude lower than that of snow. It should be noted that other factors such as material velocity, orientation to sound beam and surface roughness can affect the reflected signal amplitude. The results of this test are only meant to prove the feasibility of using air coupled ultrasonics in detecting snow on guideways by approximating the material characteristics of snow. The results do prove the feasibility that snow can be detected using this technique. However, tests using actual snow conditions should be performed before implementing such a system.

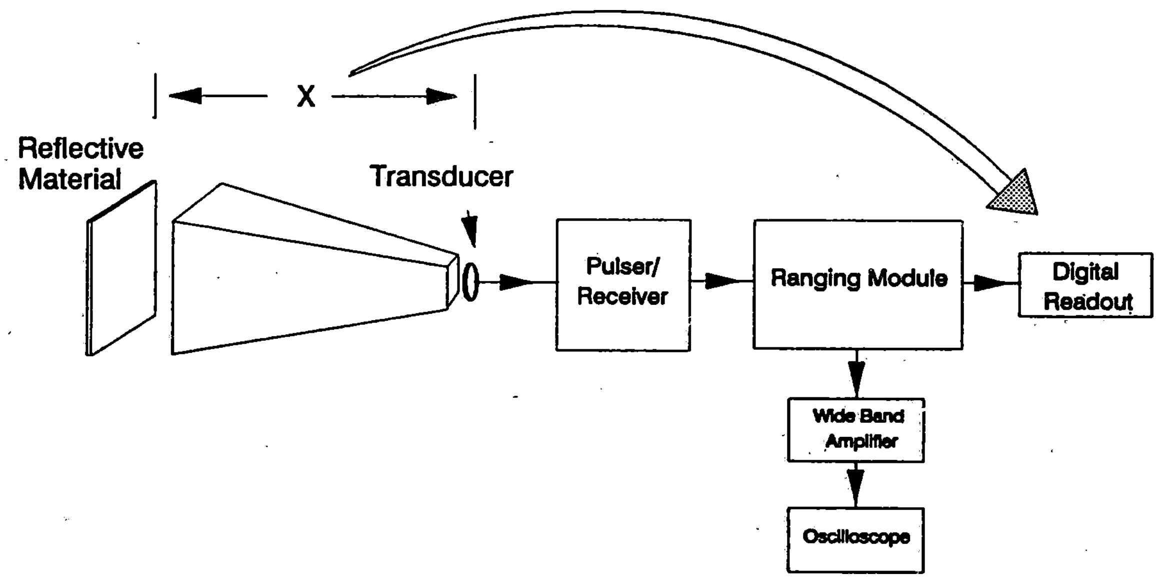


Figure A2-1: Test setup used for determining the feasibility of using air coupled ultrasonics for snow detection.

Appendix #A3 - Effect of Magnetic Fields on Piezoelectric Transducers

Introduction / Goals:

Piezoelectric sensors are commonly used in areas containing adverse environmental conditions. However, unlike most applications, use of these sensors in a Maglev guideway environment could subject them to intense magnetic fields. The effect on piezoelectric crystals when subjected to a strong magnetic field is not clearly documented. It is the purpose of this experiment to provide some information concerning this potential problem. The results of this study could influence the placement of such sensors on or around the guideway and the expected reliability during the passing of a Maglev train. It should be noted that the magnetic fields used in this study may not be as intense as would be expected for a sensor in an actual Maglev environment.

Background / Method:

The magnet used for this experiment is shown in Figure A3-1. The magnetic field produced by this permanent magnet was measured to be approximately 5,500 gauss (0.55 tesla) using an incremental gaussmeter. A spacing of approximately 1 inch existed between the poles of the magnetic providing adequate space for the transducer.

The transducer utilized a 1/2 inch diameter polarized ceramic crystal that operated at a harmonic frequency of 2.25 MHz. Coupled to the face of the transducer was a cylindrical section of plexiglass approximately 1/2 inch in length. The surface of the plexiglass opposite the transducer was used as the reflecting surface for these tests. Ultrasound produced by the transducer was allowed to propagate through the plexiglass, reflect off of the opposite surface and return to the transducer where it was detected. The material was small enough so that both it and the transducer could be moved, simultaneously through the magnetic field. The transducer was connected to a pulser/receiver unit that both excited the transducer with a high voltage spike as well as provided amplification for the resulting signals. An oscilloscope was used to monitor the reflected signal. Figure A3-2 illustrates the setup used for this experiment. The response of the transducer was monitored both in and out of the magnetic field as well as during transition into the field. Waveform parameters such as frequency and amplitude of the reflected signal were monitored. Any increase in noise level of the received signals was also noted.

Results:

This test indicated that the presence of a 5500 gauss magnetic field does have an affect on the response characteristics of polarized ceramic piezoelectric material. Although small, this affect is distinct and measurable. Figure A3-3 shows A-scans where the transducer is subjected to a) no magnetic field and b) 5500 gauss magnetic field. The presence of the magnetic field appeared to affect the characteristics of the piezoelectric element in two ways; frequency and damping.

The frequency of the received signal increased when the transducer was placed in the magnetic field. This frequency shift was measured to be an increase of approximately 15% for the 2.25 MHz transducer. This increase in frequency did not represent a major problem since the bandwidth of this transducer was relatively broad. In addition, the frequency of the probe increased with an increase in the intensity of the magnetic field.

The amplitude of the reflected signal decreased when the transducer was placed in the magnetic field. The piezoelectric crystal appeared to be dampened by the magnetic field. The damping effect caused a decrease in amplitude of approximately 2 dB. The amplitude of the reflected signal decreased with an increase in the intensity of the magnetic field.

There were no changes observed in the noise level of the signal while in or during the transition into the magnetic field.

Conclusions / Recommendations:

This experiment indicated that the response of piezoelectric sensors may be affected by the magnetic fields found on or near Maglev guideways. Both damping and an apparent increase in frequency response of the crystal were observed. However, the affects measured during this experiment were not severe enough to adversely effect the functionality of these types of sensors. However in the presence of extremely high magnetic fields, these effects could become a significant factor in the effectiveness of these sensors. Therefore, tests should be performed using actual guideway conditions in order to determine the significance of these effects at greater magnetic intensities.

The observed effects are not unexpected, and at this field strength are not sufficient to interfere with the operation of the unit, since the effect would be a transitory loss of sensitivity when a bogie is close to the transducer. The speed of sound in solids is much greater than the speed of the vehicle, so any sounds emitted when the field is not applied to the sensor would be completely unaffected.

The equivalent circuit of a piezoelectric resonator is a series R, L, C circuit in parallel with a capacitance C_0. The C_0 capacitance is formed by the electrodes, the L and C are determined by the piezoelectric and elastic constants and geometry of the resonator, and R is the loss term. The resonant frequency is the frequency at which the impedance is real (the imaginary component is zero). The observed increase in damping means an increase in R, which has a small effect on the resonant frequency. A likely mechanism for the increased damping is simply that when the crystal is excited the electrodes attached to the faces of the crystal are also moving with the crystal faces. The electrodes are then moving conductors in a magnetic field, generating eddy currents and so dissipating energy.

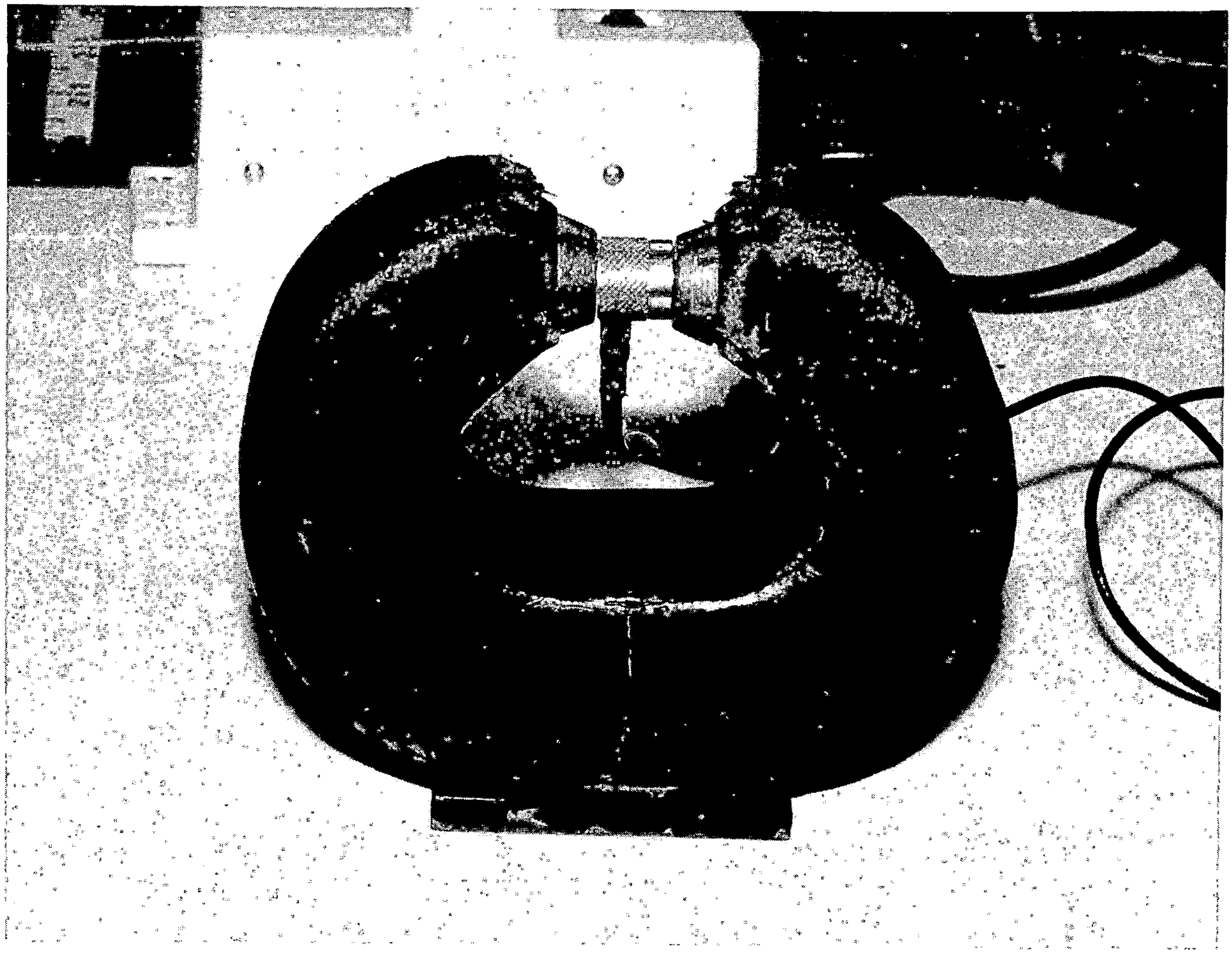


Figure A3-1: 5500 gauss permanent magnet used in experiment.

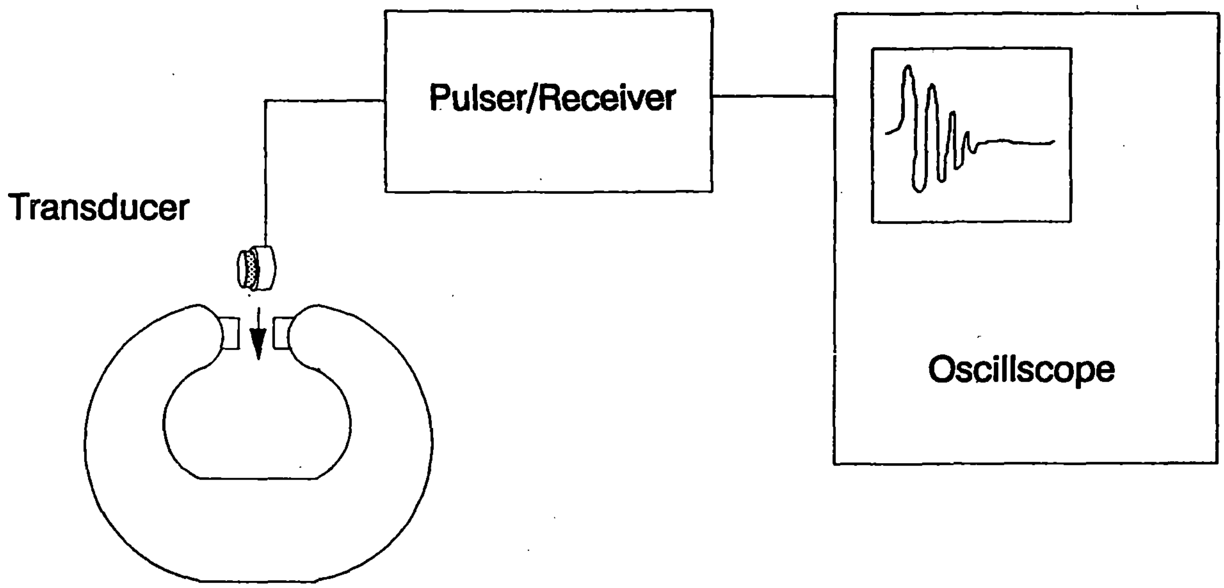
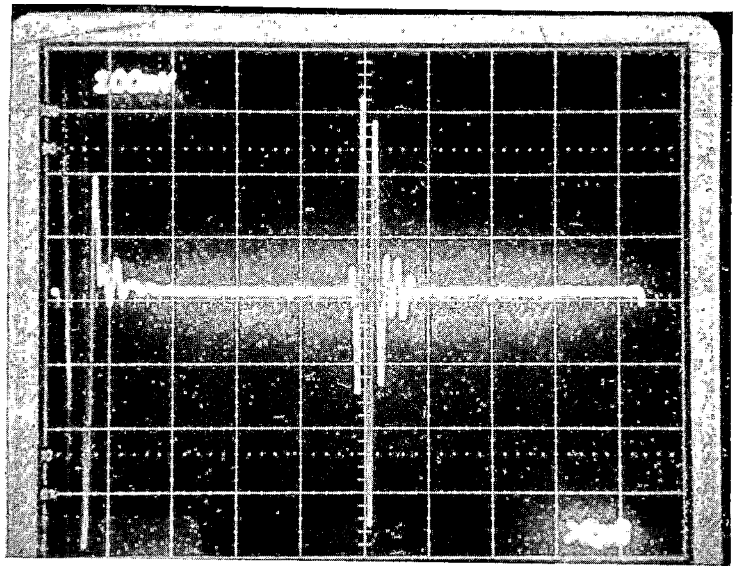


Figure A3-2: Test setup used for subjecting piezoelectric transducers to magnetic fields.

a)



b)

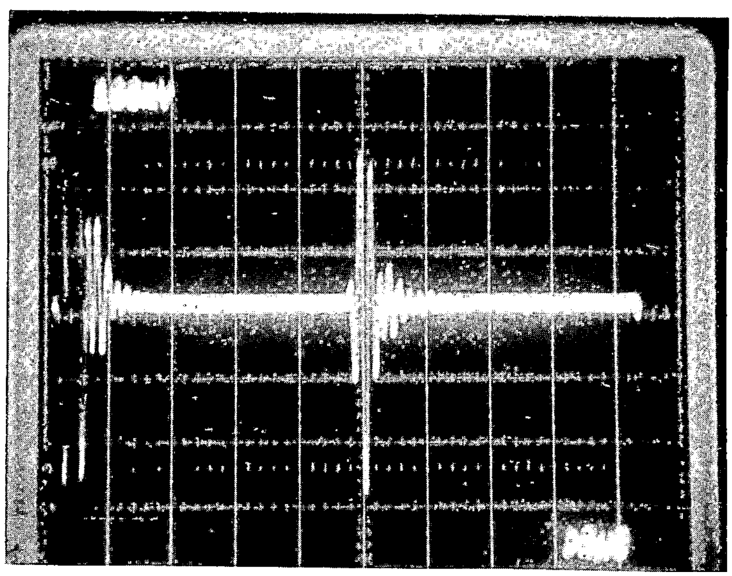


Figure A3-3: Ultrasonic signals obtained in a) no magnetic field and b) 5500 gauss magnetic field.

Appendix A4 -- Attenuative Behavior of Acoustic Emissions in Railroad Rail

Introduction:

The detectability of a typical acoustic emission (AE) event is, for the most part, governed by three primary signal characteristics, namely signal strength, frequency, and attenuation. Ample AE signal strength is imperative to overcome typical background noises and to provide AE activity reasonably detectable at some distance from the actual AE source. The sources of the AE activity as well as the attenuation properties of the propagating medium also play an important role in the detection process.

Typically, AE events are broadband in nature; the signals associated with AE activity contain a spectrum of different frequencies. In light of this, it would first appear that detection capability would present little difficulty since the monitoring system could theoretically operate at any of a wealth of frequencies. However, it is well known that the higher frequency components of a given signal dissipate energy and attenuate faster than the lower frequency portions; the acoustic emission spectrum usually contains higher frequencies at the emitting source than at some distance from the source. Thus, upper end (high) monitoring frequencies become a function of sensor-to-source distances in light of the expected attenuation properties of the material or propagation medium of interest. Lower end monitoring frequencies, as expected, remain driven by background noises associated with the system.

The goal of the experiment outlined below was to reasonably predict attenuation properties representative of those expected from a maglev guideway and hence provide insight into sensor frequency and density requirements. A typical railroad track was utilized to represent the guideway structure. This is on the assumption that there will be continuous steel reinforcing available on which to mount sensors.

Methodology:

In order to determine the attenuation properties, broadband AE transducers were coupled to the rail (see Figure A4-1) and subsequent artificial AE sources were produced on the rail at increasing distances from the transducer (Figure A4-2). Note that the artificial sources were generated from breaking pencil leads (0.5 mm No. 2 Pentel) against the structure. The pencil lead sources are an accepted method of producing simulated AE events as outlined in an ASTM standard.

The signals resulting from the artificial sources were then acquired and analyzed with a real-time AE system as well as a digital data acquisition and signal processing software package as shown in Figure A4-3. Results of the attenuation study are outlined below.

Results:

Spectra were collected from pencil breaks every foot (0.3 m) from 1 to 39 feet (0.3 to 11.9 m) from the sensor. The individual power spectra had very complex fine structure because of the complex interactions of the various wave modes. The spectra shown in this report were generated by summing the power in 48.8 kHz wide bands to obtain more intelligible figures. Figure A4-4 shows two power spectra collected at different distances. They have each been normalized to their peak amplitudes. The upper trace is the closer signal and it has, as expected, more power at higher frequencies than the more distant sample.

Figure A4-5 is a psuedo-three-dimensional plot of all 39 spectra. It looks something like a mountain range. The upper right corner is the lowest frequency and the closest source. Moving along the upper ridge, to the left, are spectra at increasingly greater distances. Moving down the slope, to the right, are responses at higher frequencies. Along the top of the ridge a straight line is visible. This is the frequency band (about 195 to 244 kHz) that was used to normalize each of the spectra. The overall shape of each spectrum is determined by the source spectrum, the propagation effects, and the sensor response spectrum, but differences between spectra are caused by propagation effects. The most striking feature of this figure is the series of steps down from the peak power to the background level. These are separated by 128 kHz, and are caused by interference between the arriving waves and the reflection from the end of the rail, about 1 cm away.

From these normalized spectra, it was possible to construct curves of power versus distance at each frequency, and determine the loss in dB per unit distance at each frequency. When this attenuation constant is graphed against frequency, is is found to vary with the square of the frequency as expected. For this rail, the attenuation is 0.1 dB/ft (0.3 dB/m) at 220 kHz and 1 dB/ft (3 dB/m) at 690 kHz. This is 10 times the loss at 3.1 times the frequency, in excellent agreement with the square law.

Conclusions:

Based on information derived from this study, it is estimated that each 100 feet of guideway could be acoustically monitored with one acoustic emission sensor provided background noises are such that a 250-300 kHz transducer could be utilized. Some experimentation will be necessary to determine the damping effects of concrete on waves propagating in reinforcing bars.

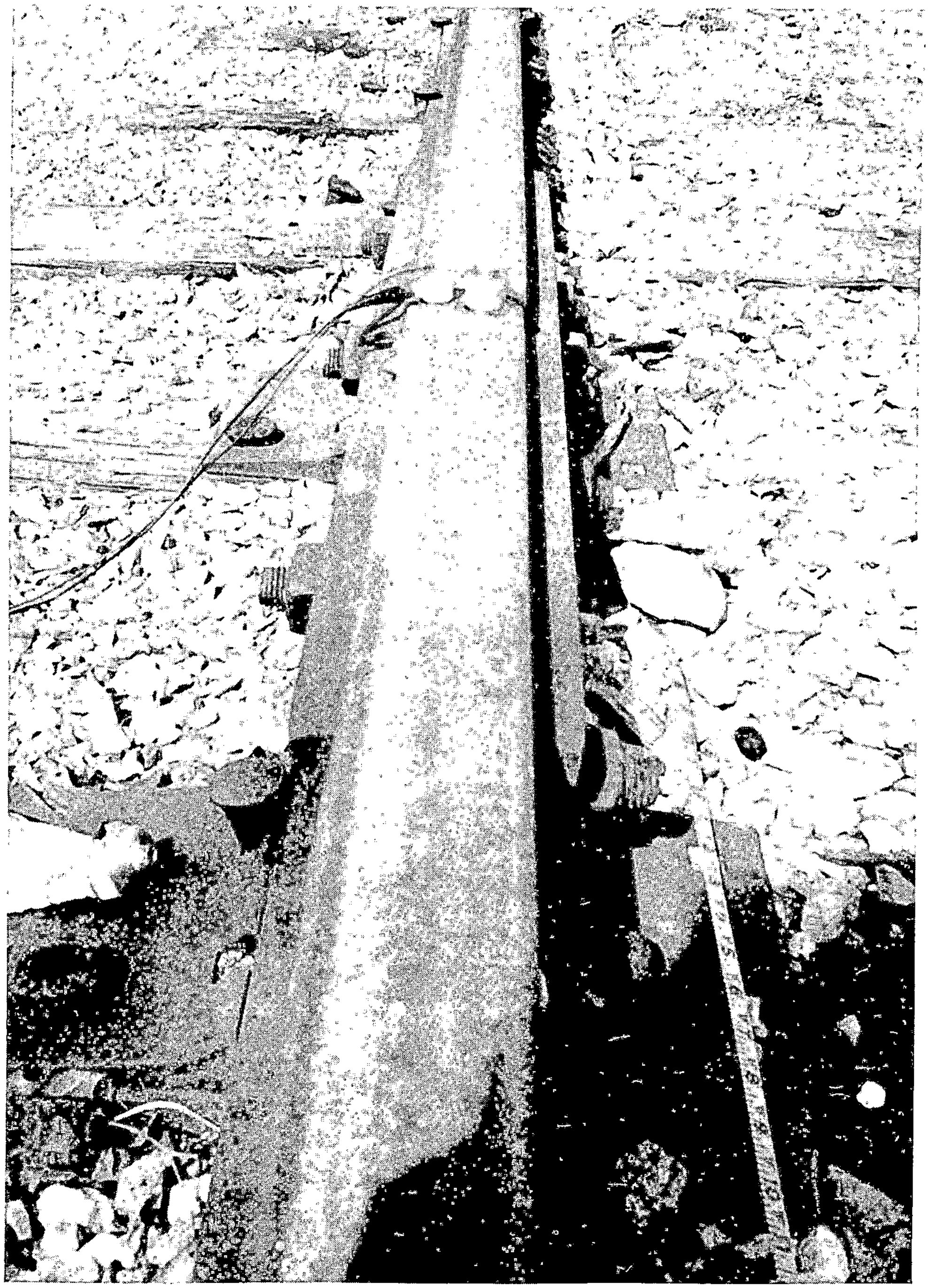


Figure A4-1. AE Sensor Locations

Figure A4-2. Artificially Inducing Acoustic Emissions

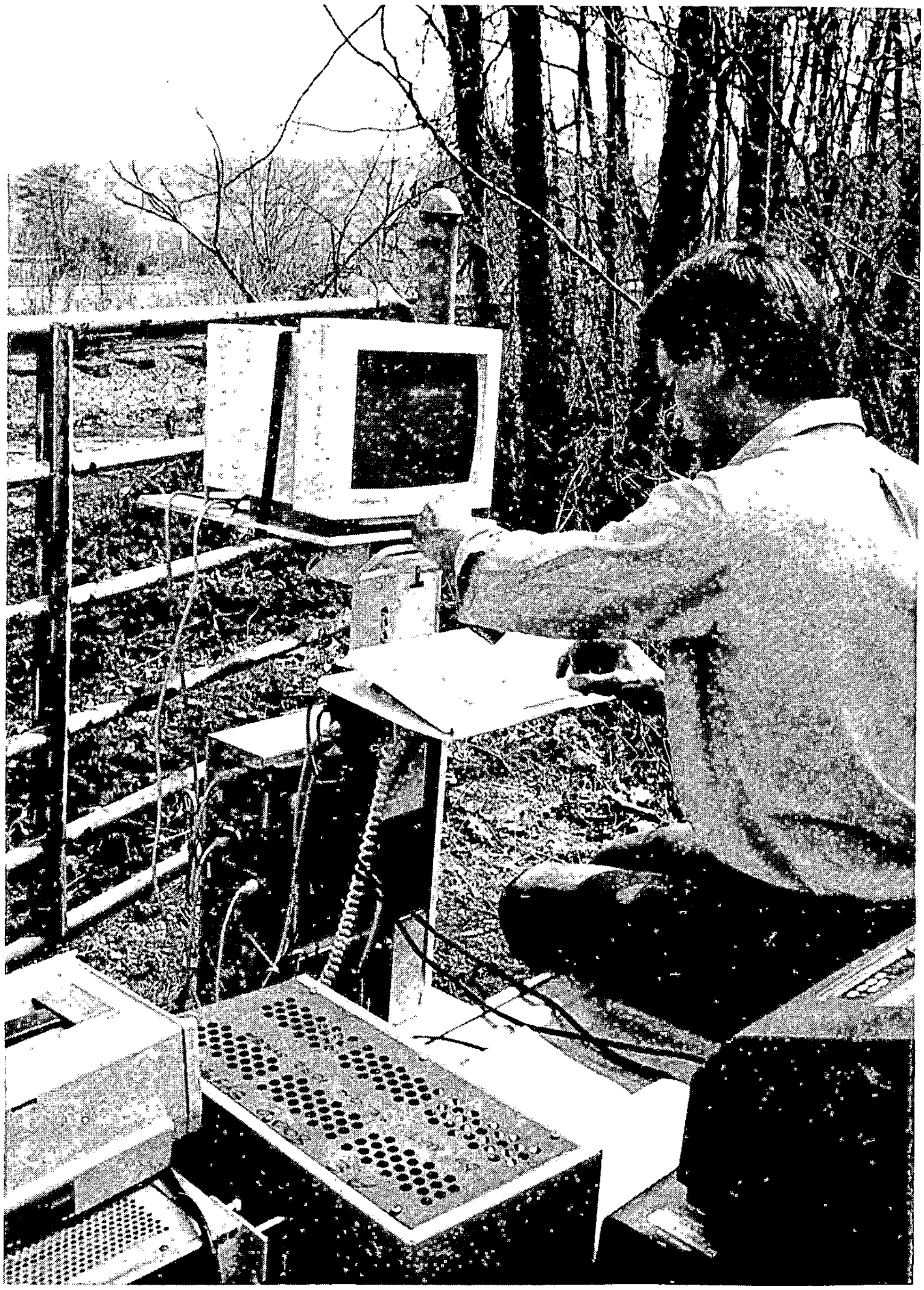


Figure A4-3. Acoustic Emission Test System

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