INDUSTRIAL NOISE CONTROL

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PREFACE

Controlling noise has been a traditional challenge in the industrial and business world. There are many reasons to be concerned about noise because studies have shown that workers exposed to high noise levels have low working efficiency. Noise can furthermore be responsible for a wide range of tension, heart disorders, and circulatory problems.

This book is intended for use by those faced with noise problems in the workplace. It should be of use to consultants, managers, and engineers, as well as all those concerned with noise control. It is written in technical language to facilitate its use and stresses the practical rather than the theoretical. Regulations and the law require that employers provide a noise control program whenever employees work in an environment exposing them to noise hazards. Hopefully, this book will provide the necessary information for a safer and more productive work environment.

The author is indebted and acknowledges the following individuals who provided information contained in this book and an earlier work by the author:

Anthony J. Schneider	Chapter 3—Acoustics Chapter 7—Vibration Chapter 10—Instrumentation
David Marsh	Chapter 10—Instrumentation
Nicholas P. Cheremisinoff	Chapter 9—Ventilation Systems
E.J. Bonano	Chapter 9—Ventilation Systems
Charles E. Wilson	Chapter 12—Interpolation and Mapping

Major contributions by these experts in the accompanying chapters make this book a comprehensive tool for those concerned with noise.

Since most books on noise are oriented architecturally—not industrially—this book will be especially valuable to those who may have found it difficult to find practical solutions to noise control problems in industry. This includes safety, mechanical, civil, environmental, and chemical engineers, plant and maintenance managers, and industrial hygienists and managers.

Paul N. Cheremisinoff

CONTENTS

PREFACE

1 *NOISE EFFECTS* 1

THE HUMAN EAR 2
THE EFFECTS OF NOISE ON THE HUMAN EAR 4
TOLERANCES 4
DANGEROUS PROPERTIES OF NOISE 4
NOISE AFFECTS THE MIND AND OUTPUT 6
EFFECTS ON THE HUMAN BODY 7
AUDIOGRAMS 8
EFFECTS OF VIBRATION ON MAN 8

2 *NOISE REGULATION* 11

OCCUPATIONAL SAFETY AND HEALTH ACT (OSHA) 11
Responsibilities of Employers 12
Responsibilities of Employees 12
Administration 13
OSHA Standards 13
OSHA'S REGULATIONS ON NOISE CONTROL 18
Impulse or Impact Noise 19
Variable Noise 19
Engineering Control Measures 19
Administrative Controls 20
WALSH-HEALEY PUBLIC CONTRACTS ACT 21
PRIMER ON OSHA 22
Purpose of the Act 22
Businesses Affected 22
Duties of Employers 23
Duties and Rights of Employees 23
Occupational Safety and Health Standards 24
Administration 24

Complaints of Violations 24
Inspections 25
Notification of Proposed Penalty 25
Contesting a Citation 25
Time for Abatement of Hazards 26
Variances 26
Failure to Correct Violations within Allowed Time 26
Penalties for Violations 26
Recordkeeping Requirements 27
Statistics 27
Imminent Dangers 27
Protection Against Harassment 27
What an Employer Should be Doing 27
GUIDE FOR IMPLEMENTATION 28
Policy 28
Procedures 28
Recordkeeping Requirements 29
NOISE ENFORCEMENT DIVISION 30
U.S. ENVIRONMENTAL PROTECTION AGENCY 30

3 ACOUSTICS *32*

NATURE OF SOUND 32
THE SOUND FIELD 35
SCALES FOR MEASUREMENTS—THE DECIBEL 38
LOUDNESS AND OBJECTIVE MEASUREMENTS 39
COMPLEX NOISE 42

4 ENGINEERING CONTROLS AND DESIGN *44*

MAINTENANCE 44
MACHINES SUBSTITUTION 46
PROCESS SUBSTITUTION 47
VIBRATION DAMPING 47
EXCESSIVE VIBRATION CAUSES 48
ISOLATION AND DAMPING OF VIBRATION 50
INCLUSION OF NOISE LEVEL SPECIFICATIONS WHEN ORDERING NEW EQUIPMENT 52
ISOLATING NOISE SOURCES 52
OPERATOR ISOLATION 54
SYSTEMS DESIGN 54

5 PERSONAL SAFETY *57*

ACOUSTIC PROBLEM 57

EAR PROTECTION 59
Insert Type 61
MUFF-TYPE PROTECTORS 62
COMBINED USE OF MUFFS AND INSERTS 64
COMMUNICATION WHILE WEARING EAR PROTECTORS 64
EAR PROTECTION PROGRAM 66

6 *ENCLOSURES AND BARRIERS* *68*

LEAD AS A NOISE BARRIER 68
PLENUM BARRIERS 70
HOW TO INSTALL PLENUM BARRIERS 71
BARRIERS AROUND PIPES AND WIRES 72
BARRIERS AROUND RECTANGULAR DUCTWORK 73
BARRIERS UNDER TWO-WAY JOIST SYSTEMS 78
HIGH TRANSMISSION LOSS CEILINGS 79
ADDITIONAL SOUND-CONTROL MATERIALS 80
ACOUSTICAL FOAMS 80
FOAM WITH POLYMER FILM SURFACE 82
ACOUSTICAL PANEL 82
POLYURETHANE FOAM 84
NYLON IN NOISE REDUCTION 87
Nylon Gears 87
PVC FILM 88
DAMPING COMPOUND 89
SILENCERS AND SUPPRESSOR 90

7 *VIBRATION* *93*

NATURE OF VIBRATION 93
Periodic Functions 93
Random Vibration 95
Transient Vibration 96
SOURCES OF VIBRATION 96
VIBRATION EFFECTS 97
VIBRATION MEASUREMENT 97
DISPLACEMENT, VELOCITY AND ACCELERATION 99
PEAK, AVERAGE, AND RMS VALUES 103
PRINCIPLES OF VIBRATION TRANSDUCERS 104
Displacement Measurement 104
Velocity Measurement 106
VIBRATION METERS 109

8 VIBRATION CONTROL *111*

PADS AND MOUNTS 111
RUBBER ISOLATORS 112
SPRING SYSTEMS 113
Air Springs for Vibration Control 113
ADJUSTABLE DAMPERS 114
TYPES OF VIBRATION MOUNTS 116
BASIC INSTALLATION PRINCIPLES 117
SEVERAL TYPES OF INDUSTRIAL MOUNTINGS 119
SHAFT COUPLINGS 126
VIBRATION PLATES 127
BLOCKS 128
Some Applications for Isolators 128

9 VENTILATING SYSTEMS *131*

Ventilating Systems 131
Air-Conditioning Systems 132
NOISE CRITERIA 133
Loudness and Loudness Level 133
Speech Interference Level 133
NC and PNC Ratings 133
Noise Pollution Level (NPL) 135
A-Weighted Sound Level (L_A) 135
Insertion Loss 135
Transmission Loss (L_{TL}) 135
Dynamic Transmission Loss 135
MEASUREMENT TECHNIQUES 136
NOISE REDUCTION 137

10 INSTRUMENTATION *141*

MICROPHONES 141
SOUND LEVEL METERS 146
CALIBRATION 150
THE ACOUSTICAL MEASUREMENT 151
DOSIMETERS 151
FREQUENCY ANALYZERS 152
AMPLITUDE DISTRIBUTION ANALYZERS 153

11 AUDIOMETRIC TESTING AND DOSIMETERS *156*

AUDIOMETERS 156
ACCURACY 157

RECORDS 158
AUDIOMETRIC TEST BOOTHS 158
ALTERNATE PROGRAMS 160
DOSIMETERS 161

12 INTERPOLATION AND MAPPING *162*

NOISE LEVEL AND FREQUENCY WEIGHTING 162
INDUSTRIAL HEARING DAMAGE RISK 163
COMMUNITY NOISE FROM INDUSTRIAL SOURCES 163
NOISE CONTROL 163
COMPLIANCE WITH CODES AND STANDARDS 163
NOISE-LEVEL MAPPING 164
POINT SOURCES OF NOISE 164
THE INVERSE SQUARE LAW 165
THE NEAR AND REVERBERANT FIELD 165
PLOTTING POINT SOURCE NOISE LEVELS 166
LINE SOURCES OF NOISE 168
THE INVERSE DISTANCE LAW 168
PLOTTING LINE-SOURCE NOISE LEVELS 169
COMBINED NOISE SOURCES 170
NOISE CONTOUR MAPPING FOR LINE AND POINT SOURCES 172
NOISE CONTOURS FOR COMBINED NOISE SOURCES 173

GLOSSARY **174**

INDEX 186

1 NOISE EFFECTS

Every industry, trade, occupation, and process using equipment, methods, apparatus, or materials that generate noise above certain levels involve elements of danger to the health and safety of employees and other persons frequenting such areas. Medical studies and other sources of evidence indicate that noise having certain characteristics affects the auditory system of the human body, causing loss of hearing. Loss of hearing occurs due to the cumulative effect of exposure to sound above a maximum intensity and over a maximum duration in a given period of time.

When employees are subjected to sound exceeding prescribed levels, employers must institute feasible engineering or administrative controls designed to decrease noise levels in working areas. If given controls fail to reduce noise levels below prescribed levels personal protective equipment must be provided and its proper use by the exposed personnel must be enforced by management. To monitor the effectiveness of the engineering and administrative controls, and the proper use and effectiveness of personal protective equipment, a continuing effective hearing conservation program should be administered.

The three noise control measures may be defined as follows: (1) *Engineering controls* are those which reduce the sound intensity either at the source of the noise or in the hearing zone of the worker; (2) *administrative controls* are those which limit the duration of the workers' exposure to noise levels above 90 dBA to the table of Permissible Noise Exposures; and (3) *personal protective equipment* (ear muffs, plugs, and so on) shall be provided and used to reduce sound levels to permissible levels. It is important to note that the use of personal protective equipment is considered to be an interim measure and is not acceptable as a permanent solution to noise problems.

Surveys indicate that more than half of industrial machines generate noise levels of 90 to 100 decibels. This presents a definite health hazard to workers. Noise-induced hearing loss is dangerous because, once incurred, normal hearing can almost never be fully restored.

Four options are open in arresting this problem. The best is to reduce the noise level at its source. However, this is not always feasible. Reduction of noise generated by the machine may be accomplished by:

- proper acoustical design in machinery
- modifying existing machine design
- muffling
- changing the process entirely

A second approach is to reduce the amount of sound transmitted through the plant. This can be accomplished by:

- increasing the distance between the work vicinity and source
- installing acoustical barriers between the work area and sound source
- mounting equipment on vibration stands to reduce noise transmission through the building

This second list may prove to be costly and ineffective on the noise levels in the immediate area.

The third choice is to revise operational procedures. This may involve:

- changing job schedules,
- rotating personnel,
- providing longer or more frequent work breaks.

This approach cuts down on continuous noise levels; however, it may be uneconomical.

A final approach is to provide the individual with personal ear protection. This seems to be the simplest solution, both economically and to the machine operator; however, there are certain drawbacks. The majority of individuals find personal ear protection devices uncomfortable, irritating and, in many cases, cumbersome.

One of the major problems facing industry today is noise pollution. Data show that over 10 percent of the U.S. work force suffers some hearing impairment due to exposure to high noise levels.

THE HUMAN EAR

The human ear diagrammed in Figure 1-1 can be broken down into three basic parts. The *outer ear* contains the external auditory canal which functionally carries sound waves to the tympanic membrane, or eardrum. The *middle ear* begins with the eardrum which is a strong flexible tissue with a cone-type construction. When sound waves travel through the external auditory canal and hit the eardrum, they will cause it to vibrate. Also, part of the middle

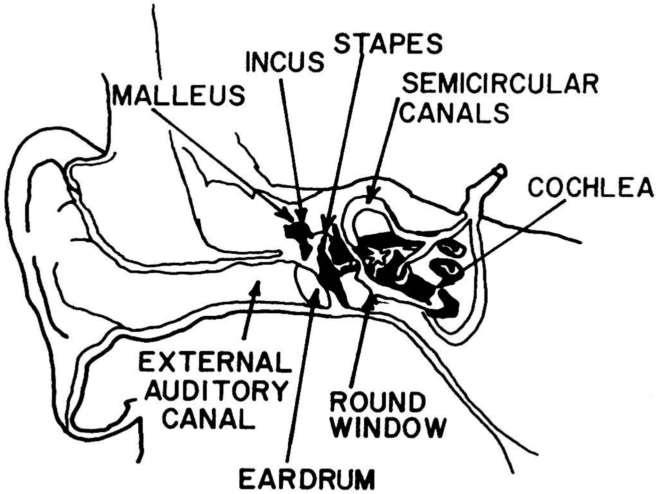

Figure 1-1 Diagram of the human ear.

ear is the malleus or hammer, which is a bone that is connected to the eardrum. The malleus is linked to two other bones which move within a very small space. This assemblage of bones, the smallest in the human body, are known as the ossicles and transmit sound waves to the *inner ear* from the eardrum. They also modify sound by either amplifying or diminishing it to protect the inner ear. At the other end of these bones is the foot of the stapes which directly transmits sound to the *inner ear* and is approximately one thirtieth the area of the eardrum.

We can see that the middle ear regulates the level of sound that enters the external auditory canal, and also protects the inner ear. It is approximately 2 cm^3 in volume, filled with air which dampens the low-frequency rocking of the ossicles. In addition to this arrangement, there are two muscles attached to the stapes and the malleus which are known as the tensor tympani and the stapedius muscles. The function of these muscles is to tighten the eardrum and the motion of the ossicles, thereby lessening the efficiency of sound transmission. This function is known as the acoustic reflex and is carried out by command of the brain just after every loud sound reaches the eardrum.

The inner ear is a very complex system of boney, fluid-filled crevices lying deep inside the temple. The components which make up the inner ear have nothing to do with hearing but are responsible for our senses. One component is the utricle, which gives us our sense of acceleration and gravity. Another is an arrangement of three semicircular canals which gives us our sense of orientation, space, and balance. The part of the ear with which we actually hear is called the cochlea. When sound waves travel through the external auditory canal, the foot of the stapes bone knocks against the oval window, which is a wide opening in the cochlea, and sound is transmitted to the liquid inside. The round window that lies just below the oval window is an elastic membrane which is the final component that sound waves reach in the human ear.

THE EFFECTS OF NOISE ON THE HUMAN EAR

The ear has its own defense mechanism against noise—the acoustic reflex. However, this reflex has vital weak points in its defenses. First the muscles within the middle ear can become fatigued and slow if overused. In persons who work in an environment with high noise levels, these muscles will gradually lose their strength and thus more noise will reach the inner ear. Second, these muscles can be affected by chemicals within the working environment. Finally, the acoustic reflex is an ear-to-brain-to-ear circuit which takes at least .009 second to perform.

Persons with poor acoustic reflex usually are subjected to temporary hearing loss when they come in contact with a loud noise. Much of the temporary hearing loss caused by noise occurs during the first hour of exposure. Recovery of hearing can be complete several hours after the noise stops. In short, the ear will recover to its full hearing potential after its muscles have had time to rest. However, the period of recovery depends on individual variation and the level of noise which caused the deafness.

TOLERANCES

Persons in different age groups have different tolerances to various noise levels. There have been many investigations made of the threshold of hearing. When young people who have good hearing ability are tested, a characteristic known as the minimum audible field (MAF) is obtained. This characteristic indicates the level of a tone that can just be detected in very quiet surroundings under free-field conditions as a function of frequency of the tone. Under free-field conditions the sound source is equidistant from any objects including the ground. Therefore, the sound pressure is distributed uniformly in all directions, and doubling the distance from the source will cut the sound pressure in half. At low frequencies sound-pressure level must be high before a tone can be detected. At a sound level of about 120 dB a listener would be very uncomfortable. At 140 dB the listener would experience pain.

DANGEROUS PROPERTIES OF NOISE

Noises that pose the greatest threat to the human body are those which are the highest pitched, loudest, poorest in tone, and longest lasting. Another dangerous type of sound—capable of rupturing the eardrum—is the sound of an explosion. However, when only the eardrum is ruptured the inner and middle ear are protected. In time, the eardrum heals and full hearing is usually restored.

Deafness due to noise usually occurs in conjunction with a fairly common hearing disorder known as *recruitment of loudness*. In a person who has this disorder, the zone between what can just be heard and what is too loud is much narrower than normal. Persons with this affliction would have much difficulty in detecting not only weak sounds but sounds which are fully audible to the normal ear. However, the recruitment ear will retain its sensitivity for loud sound levels. Another problem that a person with recruited ears would face is the discomfort of hearing aids. The hearing aid is a microphone that transmits sounds from the surrounding environment to an amplifier connected to a small loudspeaker built into an earplug and aimed at the eardrum. The major problem is the sounds entering the hearing aid have to be amplified enough to be heard loudly, and at that level the sound may produce discomfort (see Table 1-1).

Table 1-1 Percentage of People with Impaired Hearing in a Noise-Exposed Group

Equivalent Continuous Sound Level (dBA)	Years of Exposure									
	0	5	10	15	20	25	30	35	40	45
80 Risk, %	0	0	0	0	0	0	0	0	0	0
% with impaired hearing	1	2	3	5	7	10	14	21	33	50
85 Risk, %	0	1	3	5	6	7	8	9	10	7
% with impaired hearing	1	3	6	9	13	17	22	30	43	57
90 Risk, %	0	4	10	14	16	16	18	20	21	15
% with impaired hearing	1	6	13	18	22	26	32	41	54	65
95 Risk, %	0	7	17	24	28	29	31	32	29	23
% with impaired hearing	1	9	20	28	34	39	45	53	62	73
100 Risk, %	0	12	29	37	42	43	44	44	41	33
% with impaired hearing	1	14	32	42	48	53	58	65	74	83
105 Risk, %	0	18	42	53	58	60	62	61	54	41
% with impaired hearing	1	20	45	57	64	70	76	82	87	91
110 Risk, %	0	26	55	71	78	78	77	72	62	45
% with impaired hearing	1	28	58	75	84	88	91	93	95	95
115 Risk, %	0	36	71	83	87	84	81	75	64	47
% with impaired hearing	1	38	74	87	93	94	95	96	97	97

Note: Percentage of people with impaired hearing in a nonnoise-exposed group is equal to percentage in a group exposed to continuous sound levels below 80 dBA. Age = 18 years + years of exposure.

Researchers have analyzed noise and its effects on the human ear and have come up with several properties of noise which contribute to the loss of hearing. One of these properties is the *overall sound level of the noise spectrum*. Here it has been noted that noise whose overall sound level is below 80 dB is reasonably safe. However, many industrial noise levels are above 80 dB. To say how these levels would affect the personnel, more specific information on the types of noise would be required.

Another dangerous property of industrial noise is the shape of the noise spectrum. Various studies have revealed that temporary hearing loss, also known as temporary threshold shift (TTS), is a function of the spectrum of the noise. The ear is specifically sensitive to frequencies above 1 kHz, and in fact most cases of hearing loss occur at these frequencies. Noise containing concentrated energy within the octave bands 600—1,200 Hz and higher is much more dangerous to the ear than noise below 600 Hz. Also, a pure tone at a specific level is more dangerous dangerous than a band of noise at the same level, both being at the same frequency.

The next dangerous property of noise is total exposure duration. When exposure to noise permanently lessens a person's sensitivity for hearing, a permanent threshold shift (PTS) has taken place. Through studies of PTS and TTS, it has been determined that the longer a person is exposed to high noise levels, the more his or her hearing ability will decrease. However, the hearing loss due to the noise may not continue until the person is totally deaf.

A final characteristic of noise that should be mentioned is the temporal distribution of noise. However, energy in noise is distributed across time and its final effect on the threshold shift is a function of total energy. It has been determined that partial noise exposures are related closely to the continuous A-weighted noise level by equal energy amounts. The relation between energy and the amount of exposure can be stated as: twice the energy (3 dBA increase) is acceptable for every halving of exposure time, without any increase in danger. Many studies have revealed that significantly high noise levels can be tolerated if exposure time is decreased sufficiently. Table 1-2 indicates permissible noise exposures according to Department of Labor regulations.

Table 1-2 Permissible Noise Exposures

Duration per Day (hours)	Sound Level dBA Slow Response
8	90
6	92
4	95
3	97
2	100
1½	102
1	105
½	110
¼ or less	115

NOISE AFFECTS THE MIND AND OUTPUT

Noise affects the mind and changes emotions and behavior in many ways. Most of the time we are unaware that noise is directly affecting our minds. It interferes with our communication, disturbs our sleep, and arouses our sense of fear. Psychologically, noise stimulates us to a nervous peak. It is overly arousing and presents too high a level of stimulation. Too much arousal causes a person to be too ready and, as a result, he or she will tend to make more mistakes. Experiments in laboratories have revealed that the presence of continuous, loud noises affects the working efficiency in laboratory tasks which require long and concentrated attention. The effects of noise increase the frequency of momentary lapses in efficiency. Noise has its effects on manual workers as well.

Since noise affects a worker's attitude and personality, it also affects his or her output. It can interfere with communication greatly; as the noise gets louder, low speech frequencies become more important. To have 90 percent speech intelligibility between two workers standing about a meter apart, the background noise of mixed frequencies cannot exceed 95 dB, and low-frequency background noise cannot exceed 105 dB (see Figure 1-2).

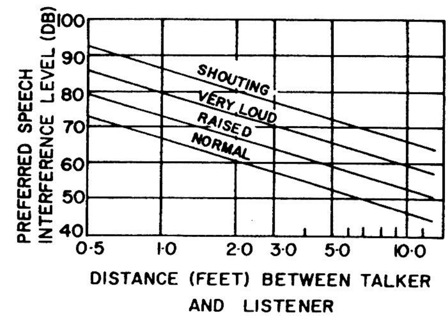

Figure 1-2 Characteristics of speech sound levels in relation to distance.

Noise can cause a decrease in the quality of work output when the background noise exceeds 90 dB. There have been studies, however, which show that the effects of noise on work output largely depend on the type of work. For instance, if a person were put on a time-consuming job that requires constant vigilance, noise would be a degenerative factor in his or her output. High noise levels would tend to cause a higher rate of mistakes and accidents rather than a direct slowdown of production. Results show that a worker's attention to the job at hand will tend to drift as noise levels increase.

EFFECTS ON THE HUMAN BODY

Noise has an explicit effect on the blood vessels, and especially the smaller ones known as precapillaries. Overall, noise makes these blood vessels narrower. It was also found that noise causes significant reductions in the blood supply to various parts of the body. This fact was discovered through a test which employed transillumination, a technique of shining a light inside the mouth of a patient and observing the redness of the cheeks on the outside. If the cheeks were red, sufficient blood was being supplied; if they were pale, there was a deficient amount of blood. When noise was administered around the patient, his or her cheeks became more pale, showing that an insufficient amount of blood was being supplied.

In tests conducted employing a ballistocardiogram used to measure the record of the heart with each beat on a patient in noisy surroundings, it was found that there was a decrease in the stroke volume of the heart. The results of such findings lead to one conclusion—that noise at all levels causes the peripheral blood vessels in the toes, fingers, skin, and abdominal organs to constrict, thereby decreasing the amount of blood normally supplied to these areas. This shrinking of the small blood vessels is known as vasoconstriction and is a reflex action generated by the nervous system. It is triggered by various body chemicals, namely adrenaline, which is produced when the body is under stress. Experiments involving finger pulse amplitude produced similar results. Experiments have revealed that 3 seconds at 87-dB noise constricted arterioles in the fingers and cut down the volume of blood by one half. After the noise stopped, it took approximately 5 minutes for the arterioles to fully recover.

Effects of noise on the blood vessels which feed the brain that were carried out employing a reograph to measure the flow of blood in the vessels leading to the brain concluded that these vessels dilate in the presence of noise. This is the reason why headaches result from listening to persistent noise. Other studies have shown that noise can induce heart attacks. When the small blood vessels are subjected to noise, there is an aggregation of red blood cells within them and the vessels contract in spasm. Thus, noise will actually cause the blood to thicken and clot and could very well lead to a heart attack.

One final part of the body affected by noise is the nervous system. Noise wears down the nervous system, breaks down our natural resistance to disease and our natural recovery, thus lowering the quality of general health.

AUDIOGRAMS

An important step toward hearing conservation in industry is the monitoring of the hearing ability of employees exposed to noise conditions. The monitoring of hearing is known as audiometry. Through audiometry it is possible to detect the least intense sound that can be heard (absolute threshold) and the minimal noticeable difference between two sounds (differential threshold) by an employee. An audiogram is the record of an employee's hearing sensitivity for absolute and differential thresholds as a number of pure-tone frequencies. Hearing sensitivity is measured in terms of the deviation in dB found in normal hearing.

An audiogram is obtained through an audiometer. This device allows pure tones at specific frequencies and intensities to be tested on the employee. There are many types of audiometers used by industry. They can provide frequencies of 500, 1,000, 2,000, 3,000, 4,000, and 6,000 Hz, with output levels more than 70 dB above the standard threshold level.

EFFECTS OF VIBRATION ON MAN

Vibration, like noise, also has harmful effects on the human body. We experience the discomfort of vibration while traveling in boats, cars, and planes.