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MUSIC, SPEECH AND HEARING: A COURSE IN DESCRIPTIVE ACOUSTICS

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ABSTRACT

A general education course in descriptive acoustics for students in music, speech, and environmental disciplines is described. The student background, course philosophy, and format are presented. Resource materials discussed include books, a study guide, films, audio tapes, demonstrations, walk-in laboratories, and an examination procedure that encourages reworking of the material.

INTRODUCTION

This paper discusses a one-semester, three credit-hour course in the descriptive acoustics of music and speech, designed especially for students studying the fine arts, the social sciences, or the humanities. The purpose of the paper is to describe some of our objectives and experiences in presenting the subject of acoustics to students who are not in the physical sciences.

OBJECTIVES AND PHILOSOPHY

This course is designed to fill two important objectives at Brigham Young University. First it is intended to provide a meaningful general education experience in the physical sciences, to help students in other disciplines gain some appreciation of the function and impact of science in our world. Hopefully it can effectively utilize the highly interesting and relevant phenomena associated with music, speech, and hearing as a vehicle to do this. The second objective is to provide a special service for students of music, speech, architecture, communicative disorders and rehabilitation, and other related disciplines, by giving them a physical foundation for better understanding some of the basic "tools of the trade."

To accomplish these objectives, the course is specifically designed to (1) acquaint the student with the scientific method and its limitations; (2) point out certain physical principles and show how they are applied to explain phenomena observed in music, speech, and hearing; (3) demonstrate the interaction between science, technology, and the humanities, particularly with regards to music and speech; (4) familiarize fine arts and humanities students with the nomenclature and basic concepts of acoustics, to aid them in the study of their own disciplines; and finally, (5) provide each student with interest and incentive to continue educating himself in the sciences.

One of the unique aspects of this course is the combination of music and speech. Courses in acoustics at the descriptive level often treat musical acoustics to the complete or partial exclusion of speech acoustics and vice versa. Certainly there is some justification for this when depth of treatment rather than breadth of treatment is the primary aim. However, we feel that once some of the conceptual tools have been developed, it is possible and desirable to treat both music and speech, and related aspects of environment as well. Many of the same ideas that are applicable in musical acoustics are applicable in speech acoustics and vice versa. Various physical laws, wave phenomena, and aspects of hearing are shared almost completely by both music and speech.

A question in any descriptive science course is how much, if any, mathematics should be used. We feel that it is important for a student to do some thinking in quantitative terms. Formula memorization is not required, but the student is expected to be able to give physical interpretation to some of the more important formulas and to use them in the solution of simple problems.

For example, the student is expected to be able to create complex waves from sine waves either graphically or in a tabular fashion. He is expected to use square roots to find vibration frequencies of simple vibrators and to use logarithms for expressing pressure and intensity levels. Square roots, logarithms, and sines are handled by table look-up, and the tables can be used in exams. The student is also expected to understand the relationships among symbolic or equation representations, tabulations of data, and graphical representations.

COURSE STRUCTURE

The course is divided into five major parts. The first two parts provide a general background in physics and wave phenomena and lay a foundation for the following parts on hearing, music, and speech. A more detailed outline of the material covered in the course appears in Appendix I, and is summarized in the first slide.

At the end of each part, the student is expected to pass a thirty-question multiple choice exam over the material of that part. No need is felt for a comprehensive final exam, since each exam draws heavily on the material of those which precede it. Furthermore, the lowest exam score is weighted double in computing the final grade, which tends to encourage the student to perform uniformly over all parts of the course. (Exams over a particular part can be repeated one or two times so that the foregoing procedure is not unduly harsh.)

INCENTIVES AND STUDENT MOTIVATION

Whether the student is in a course because it is required or because the course has received favorable publicity, creating and maintaining student interest and involvement is a continuing challenge which is compounded by the various backgrounds and interests of students. Largely as a result of student opinion surveys in previous offerings of the course, we have arrived at the following features as being desirable:

1. The course should be entertaining and relevant as well as instructive.
2. The course should provide as much opportunity as possible for dialogue: student-teacher and student-student.
3. Demonstrations should be used extensively with adequate explanation.
4. Opportunities should be provided for the student to gain some hands-on experience with the demonstration equipment.
5. A study guide should be provided to lead the student to face the significant questions entertained in the course.
6. Examination and grading procedures should be such as to encour-

age the student to come to grips with all aspects of the course and to rework concepts that he does not understand the first time.

RESOURCES - READINGS, STUDY GUIDE, CLASSROOM PRESENTATIONS

The resources that are used in the course are aimed at providing student incentive and motivation. Fortunately, a number of well-written textbooks exist which can be used as primary information sources, though none of them deal with both music and speech. The books which are presently required in the course are, The Acoustical Foundations of Music, by Backus, and The Speech Chain, by Denes and Pinson, both of which are excellent. Many of our students also obtain copies of Horns, Strings, and Harmony, by Benade, as a supplementary text. The books by Denes and Pinson, and Benade, are available in paperback.

In addition to these, we have been providing the students with preliminary notes from a book being written by Strong and Plitnik, which will combine aspects of music, speech, and hearing, and which arises directly from the development of this course. We also refer the students to a number of good reference books in our Reserve Library for supplementary readings. Students are encouraged to read from these several different sources and to get the flavor of the subject from different authors. (A bibliography of the main textbooks and supplementary books is listed in Appendix II.)

A study guide has also been prepared, including examples, questions, and problems. This serves the purpose of making the reading more pointed and encouraging the student to apply his reading to some of the observed phenomena in the field of sound. Students have reacted very positively toward the study guide, which gives them a rather concrete picture of what is expected of them in order to prepare for the exams and to achieve a particular grade. Once a student has established a particular level of achievement for himself, he is often willing to exert himself to achieve that level.

The other main informational resource, of course, is the teacher in his regular classroom presentations. Since the class usually has an enrollment of about seventy students, thus prohibiting unlimited question-and-answer dialogue, it becomes very important for the teacher to prepare effective presentations which are entertaining and stimulating as well as instructive.

Usually, the best presentations are those which are relevant to the student in terms of his everyday experiences. As an example of a presentation of this kind, suppose we use a blown soft drink bottle to illustrate some steps in application of scientific method. By blowing on the bottle when filled with different amounts of water, we OBSERVE that pitch (frequency) is related somehow to the amount of air present in the bottle. We can MEASURE and RECORD the frequencies and air volumes that correspond to each other. We then try to determine the relation that exists between frequency and air volume, perhaps trying several until we find one that fits. Using our tentative HYPOTHESIS, we PREDICT the frequency that should occur for some new air volume. We then perform the TEST experiment at the new volume, and compare the measured results to those which were predicted. If they fail to agree, we back off and start over at the hypothesis stage. Blowing on a soft drink bottle is something everyone has done, but the whole exercise can be made more meaningful for at least some of the students by pointing out that by "deforming" the bottle one could have a violin body or a guitar body and that the same basic relationship holds between sounding frequency and air volume.

DEMONSTRATIONS

A descriptive acoustics course lends itself extremely well to a large variety of films, audio tapes, and classroom demonstrations. Some of the films that we have found most effective are listed in Appendix III. The audio tapes we used were homemade, and tailored to our own needs. The following classroom demonstrations are representative of those we have found useful.

Demonstrations of the spectral content of various music and speech sounds are very important in this course. Hence one of our most useful tools is the spectrum analyzer, preferably a real-time analyzer. We have used both a portable hardware spectrum analyzer and computer simulations. Slides 2 and 3 show clarinet and trumpet spectra, respectively, from the computer-simulated spectrum analyzer (see Appendix IV.A.). However, a portable spectrum analyzer that can be used in class is much more versatile and is more exciting to students because they can bring in their musical instruments and get spectra immediately for them.

Electromagnetically driven vibrators--both single mass and multiple mass--have proven useful for demonstrating normal modes and resonances of vibrating systems. The two and three mass vibrators demonstrated here illustrate that all parts of a system move together in the lowest mode, that parts of the system move in opposition to one another in higher modes; and that the vibration frequencies are higher for the modes in which the system breaks up into opposing motions.

Illusions are always of interest to students. The aural illusion that you now hear on tape is analogous to the optical illusion that you see in Slide 4 (see Appendix IV.B.). In the optical illusion you always ascend the stairs when going in one direction and descend the stairs when going in the opposite direction. In the aural illusion, you hear an ascending pitch when the tone sequence is presented in one order and a descending pitch when the tone sequence is reversed.

Another exciting demonstration is that of the pitch of a complex tone with missing fundamental frequency. For instance, present a sine wave of 400 Hz and then one of 600 Hz. The 600 Hz tone has a higher pitch than the 400 Hz tone. Now present the 400 Hz and 600 Hz tones together and a pitch lower than either of the preceding pitches is heard. The periodicity or repetition rate of the combined 400 Hz and 600 Hz tones is 200 Hz corresponding to the lower pitch for the combined tones.

The notion that members of the brass family are approximately scaled versions of each other can be demonstrated by playing trumpet tones at normal speed, trombone tones speeded by a factor of two, and tuba tones speeded by a factor of four. The resulting tones all sound very trumpet-like as you can hear. (Other combinations of speeding up or slowing down produce comparable results.)

An interesting way to illustrate the significance of vocal tract shape in speech production is to construct model vocal tracts and excite them with an artificial larynx or a party noise maker. The resulting synthetic vowel sounds are somewhat unreal as you can hear, but it is quite apparent that the different modeled vocal tract shapes give rise to very different sound qualities.

Another demonstration that we have found to be both entertaining and instructive is an audio tape of degraded speech. The relative importance of different vocal tract resonances can be heard by speech synthesized with only certain ones present as illustrated on the tape. The role of the fundamental frequency can be assessed by changing it in the synthetic speech. The role of vocal tract length can be illustrated by speech synthesized with the formant frequencies about 20 percent higher than normal. (This corresponds to a shortened vocal tract that is about right for female speech when compared to male speech.)

DISCUSSION SESSIONS

In order to compensate for the limited dialogue in the lectures, informal discussion sessions are arranged so that any student can come and discuss the questions that are pertinent to him. Several discussion periods are made available each week, and are handled by the instructor or by a graduate assistant. A student is free to attend as many or as few of these sessions as he wishes. The discussion sessions individualize the help for those students who find it most needful while at the same time avoiding undue repetition for the students who do not require it. Students who have needed extra help have reacted very favorably toward the discussion sessions. It goes without saying that students appreciate personal concern and are stimulated by a person-to-person exchange. It is very exciting for student and teacher alike to have a concept come to light after some effort, and some of the real satisfactions for the students and the instructor have come from the discussion sessions. Indeed, many new approaches to explaining concepts have had their genesis in these discussions.

WALK-IN LABS

In addition to the demonstrations performed in the classroom, several student-performed demonstrations are made available in a walk-in laboratory. These have proven quite successful in terms of student involvement and understanding of key concepts even though they are optional for the student (but often with extra credit as an enticement). Typical exercises that have been made available to students are:

1. Measurement of displacement ofa moving vibrator through strobe lighting and panning of a Polaroid camera.
2. Measurement of auto speed by means of Doppler effect.
3. Measurement of noise levels in residential, business, and industrial areas.
4. Measurement of the spectra of various musical instrument tones.
5. Analysis of energy types in speech production by viewing the speech waveform on an oscilloscope.

A list of all the walk-in labs presently used is included in Appendix V.

EXAM PROCEDURE

Grading is based on exam scores. However, each exam may be repeated twice if desired, with the highest score being accepted. The student is not competing with other members of the class on the basis of a normal curve, but is striving to achieve some pre-determined level of proficiency which he has selected for himself. With some of the threat of the exam removed, it is useful as a teaching tool as well as a grading device. The opportunity to repeat exams has received very favorable response and has resulted in many students going back and reworking concepts until they understand them.

CONCLUDING COMMENTS

Teaching a course of this kind is sometimes fraught with communication difficulties. Physicists, musicians, speech pathologists, dramatists, etc., often use the same words for different things, and they do not always consider the same things important. It is challenging to try to communicate across the "terminology barrier" and the "point-of-view barrier."

Indeed, one of the exciting aspects of teaching the course has been the opportunity for looking at a subject from many different vantage points. A majority of the students in the course have indicated that they gained new insights into their own major field of study.

We feel that many of the students have added as much to our perspectives of the implications of acoustics in music and speech as we might have to theirs.

All in all, we feel that the course has been successful, and the experience of teaching it has proved to be stimulating, satisfying, and a lot of fun.

APPENDIX I - Topical Outline of the Course

Part I. Fundamentals of Physics and Vibration

A. Scientific Method

1. Modeling - Symbolic and mathematical representation
2. Inductive and deductive reasoning
3. Hypotheses, theories, laws, and limitations

B. The Laws of Motion

1. Description of motion
2. Effects of forces
3. Application to simple vibrating systems

C. The Concept of Energy

1. Types of energy
2. Conservation of energy
3. Application to vibrating systems

Part II. Characteristics of Sound Waves

A. Models of Matter

1. Molecular interaction forces
2. Mechanical wave propagation in matter

B. Wave Phenomena

1. Description of waves
2. Reflection, refraction, interference, diffraction
3. Analysis and synthesis of complex waves

C. Vibrating Structures in Music and Speech

1. Types of vibrating systems

    a. One-dimensional: strings, tubes, bars

    b. Two-dimensional: membranes, plates

    c. Three-dimensional: Helmholtz resonators, rooms

2. Normal modes, complex vibrations, resonance

D. Properties of Radiated Sound

1. Pressure, power, intensity

2. Directional effects

3. Relative motion, Doppler effect

4. Echoes, Sonar

Part III. Hearing and Environment

A. The Mechanics of Hearing

1. Ear canal resonance

2. Middle ear ossicles

3. Function of the cochlea

B. Subjective Sensations and their Physical Bases

1. Loudness and intensity

2. Pitch and frequency

3. Quality and spectral content

C. Other Aspects of Sound Perception

1. Masking and critical bandwidth

2. Binaural hearing effects

3. Combination tones, non-linearities of the ear

4. Missing fundamental, periodicity of waveforms

D. The Ear as a Determiner of Harmony

1. Musical consonance
2. Musical dissonance, role of beats
3. Musical scales

E. Hearing Impairments, Hazards, Annoyances

1. Effects of aging and disease
2. Intense sounds, exposure time
3. Annoyances, hazards, governmental regulation

F. Listening Environments

1. Reverberation time
2. Sound patterns in auditoriums
3. Noise control
4. Electronic sound reinforcement

Part IV. Acoustics of Musical Instruments

A. Stringed Instruments: excitation, vibration modes, spectra of bowed, struck, and plucked strings

B. Wind Instruments: excitation, vibration modes, spectra of woodwinds, brasses, organ pipes

C. Percussive Instruments: excitation, vibration patterns, spectra of bars, membranes, plates

D. Electronic Instruments

1. Electronic computer as a research tool
2. Music synthesizers
3. Tone modifiers, artificial reverberation
4. Electronic music instruments

E. Recording and Reproduction of Music

1. Recording environment, microphone placement
2. System fidelity
3. Listening environment, speaker placement

Part V. Acoustics of Speech

A. Mechanics of Speech Production

1. Vocal cords, periodic excitation
2. Constrictions, turbulence

B. Role of Vocal Tract

1. Formants, vocal tract resonances
2. Effect of vocal tract shape

C. Distinguishing Characteristics of Speech

1. Steady, transitory sounds
2. Phonemes and their spectral characteristics
3. Speech spectrograms

D. Prosodic Features

1. Intonation, fundamental frequency variation
2. Stress, intensity, duration
3. Tone languages
4. Emotional state of talker

E. Defects in Speech Production and Perception

1. Cleft lip or palate
2. Damaged vocal cords
3. Deafness, feedback systems
4. Sensory aids

F. Speech Degradation

1. Additive noise, peak clipping
2. Bandwidth limitations
3. Intelligibility testing

G. Future Prospects

1. Machine recognition of speech
2. Machine synthesis of speech
3. Computers as research tools

APPENDIX II - Texts and Reference Books

Required

Backus, J., The Acoustical Foundations of Music, (W. W. Norton & Co., New York, 1969).

Denes, P. B., and Pinson, E. N., The Speech Chain: The Physics and Biology of Spoken Language, (Doubleday, New York, 1973).

Recommended

Benade, A. H., Horns, Strings & Harmony, (Doubleday, New York, 1960).

Supplementary

Culver, C. A., Musical Acoustics, 4th Edition (McGraw-Hill, New York, 1956).

Fletcher, H., Speech and Hearing in Communication, (D. Van Nostrand, New York, 1953).

Miller, G. A., Language and Communication, (McGraw-Hill, New York, 1951).

Olson, H. F., Music, Physics, and Engineering, (Dover, New York, 1967).

Roederer, J. G., Introduction to the Physics and Psychophysics of Music, (Springer-Verlag, New York, 1973).

Seashore, C. E., Psychology of Music, (Dover, New York, 1967).

Stevens, S. S., and Warshofsky, F., Sound and Hearing, Life Science Series (Time, Inc., New York, 1965).

Van Bergeijk, W. A., Pierce, J. R., and David, E. E., Waves and the Ear, (Doubleday, New York, 1960).

Winckel, F., Music, Sound, and Sensation, (Dover, New York, 1967).

APPENDIX III - Some Useful Films

*Ears and Hearing, Encyclopedia Brittanica Educational Films, 1969.

*Function of the Normal Larynx, Institute for Laryngology and Voice Disorders, Inc., 1956.

Sound, Energy, and Hearing, Encyclopedia Brittanica Educational Films, 1957.

Sound Waves and their Sources, Encyclopedia Brittanica Educational Films, 1950.

The Speech Chain, (obtained from local Telephone Company office; produced by Bell Telephone Labs, and modeled after the book by Denes and Pinson).

Your Voice, Encyclopedia Brittanica Educational Films, 1947.

* These are especially good.

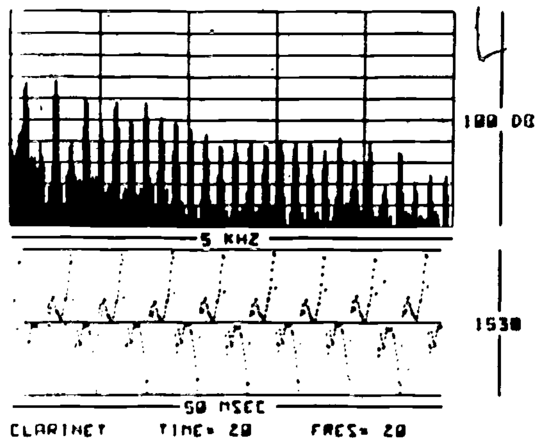
Ealing Single-Concept 8-mm Film Loops

80-218	Tacoma Narrows Bridge Collapse
80-231	Straight Wave Reflection from Straight Barriers
80-233	Reflection of Waves from Concave Barriers
80-234	Refraction of Waves
80-2371	Doppler Effect
80-240	Interference of Waves
80-252	Velocity in Circular and Simple Harmonic Motion
80-255	Velocity and Acceleration in Simple Harmonic Motion
80-266	Soap Film Oscillations

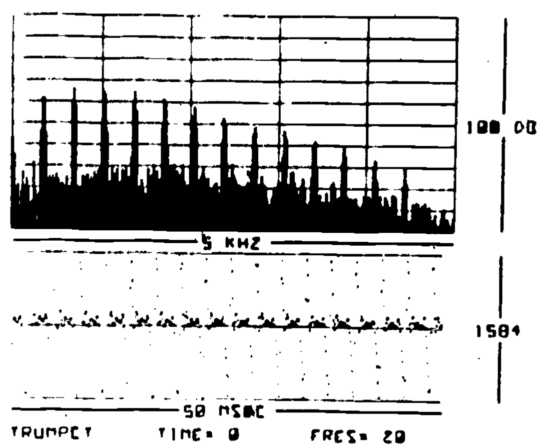
80-267	Coupled Oscillators
80-278	Simple Harmonic Motion
80-3858	Superposition
80-3866	Standing Waves on a String
80-3874	Standing Waves in a Gas
80-3890	Vibrations of a Rubber Hose
80-3924	Vibrations of a Drum
80-3932	Vibrations of a Metal Plate

APPENDIX IV

A. Spectra of Musical Instrument Tones

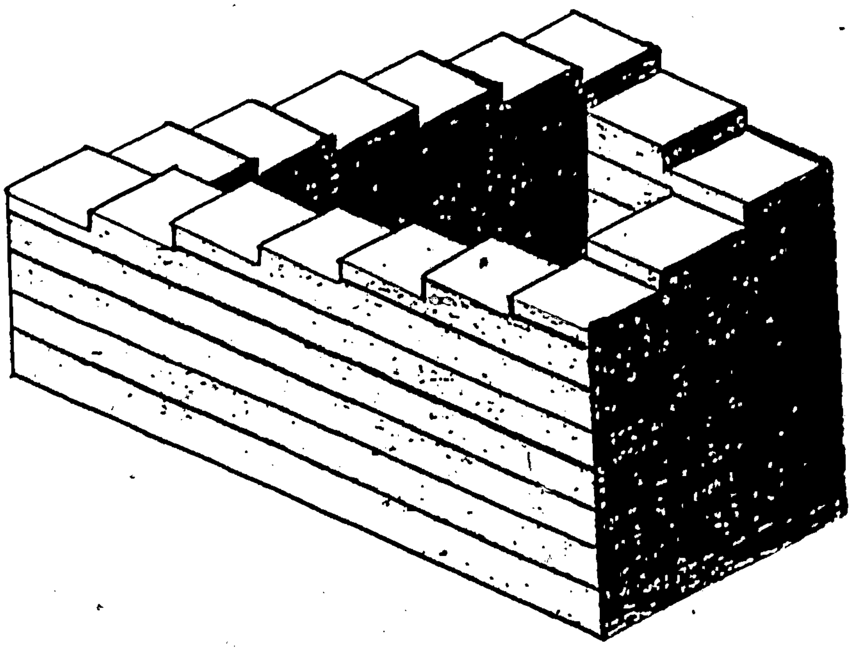


Clarinet



Trumpet

B. Optical Illusion Analogous to "Pitehup"



APPENDIX V - Walk-In Laboratories

Unit I - Fundamentals of Physics and Vibration

Measurement of Displacement of a Moving Vibrator

Transducers--Microphone, Oscilloscope, Loudspeaker, Function Generator

Simple Vibrators and Forced Vibration

Compound Vibrators and Forced Vibration

Unit II - Characteristics of Sound Waves

Measurement of Frequency, Wavelength, and Velocity

Doppler Effect

Interference of Sine Waves--Beats

Complex Waves--Analysis

Complex Waves--Synthesis

Intensity Level Variation with Distance and Direction

Standing Waves in Strings

Unit III - Hearing and Environment

Qualitative Mechanical Behavior of Inner Ear

Comparison of Subjective and Objective Measures for Hearing

Missing Fundamental and Perceived Pitch

Beat Frequency and Perceived Roughness

Sound Attenuation Through Barriers

Absorption, Sound Level, and Reverberation Time in Rooms

Noise Levels in Residential, Business, and Industrial Areas

Personal Audiogram

Unit IV - Acoustics of Musical Instruments

Spectra of String Tones

Spectra of Wind Instruments

Measurement of Attack Times

Normal Modes of Brass Instruments

Sound Velocity Variation with Temperature

Spectra of Percussive Instruments

Subtractive Tone Synthesis

Unit V - Acoustics of Speech

Analysis of Energy Types in Speech

Spectra of Speech Sounds

Construction of a Model Vocal Tract

Speech Spectrograms

Feedback in Speech

Prosodic Features of Speech