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Studies in the Physical Acoustics of Musical Instruments

A. H. Benade

Physics Department, Case Institute of Technology

I. Introductory Remarks

For approximately ten years I have carried on acoustical research as a spare time activity over and above my normal academic duties and participation in the nuclear physics research program at Case Institute. This acoustical research has proved to be most fruitful in spite of its informal basis. Because of the part-time nature of the work, only a small fraction of the results have been written up for publication. The mass of tangible results achieved, and the rate at which new problems for research have presented themselves, made it logical to consider seriously the possibility of shifting the major research emphasis from nuclear physics to musical acoustics, and in May 1963 such a change was made.

The attraction of research in musical acoustics, aside from the value of such results to the practicing musician, is the attraction of a relatively underpopulated field which requires a fair amount of experimental skill, mathematical sophistication, and the ability to "feel" the relations of the mechanical to the biological and artistic parts of the problem. The physical problems are challenging in their own right, as physics, quite apart from their musical interest, and many of them also have implications in the world of engineering design.

My professional background is well-adapted to the needs of musical research. Experience in the design of a wide variety of electronic and mechanical instruments both in the course of research and for commercial purposes combines with a reasonable fluency with modern mathematical physics to form the basis of my activities. Repeated informal research collaborations with members of the medical profession, and with workers on the problems of hearing and vision have provided a certain organizing influence on what would otherwise be a diffuse general interest in the mechanisms of living systems.

My lifelong interest in musical instruments has led to reasonable competence as an amateur musician, one who has continually cultivated his knowledge of the properties and behavior of musical instruments, as these are understood by the musician. I have made a point of acquiring some playing knowledge of any instrument before attempting to deal with it scientifically. Last but not least, my own approach, and the tradition of musical science started at Case by D. C. Miller, have made it simple to develop easy and frank relations with members of the distinguished community of professional musicians in the Cleveland area and elsewhere.

A brief outline of the history of my researches in musical acoustics is set forth below, along with a description of its present status and of plans for the future.

II. History

A. The first problem which was tackled seriously (beginning in 1954) was a study of the musical requirements which constrain the physical shape of woodwind instrument air columns. An account of this work was published in the Journal of the Acoustical Society of America - 31, 137 (1957). Subsequent experimental and theoretical work has borne out and extended the major conclusions of this paper. As a matter of fact, certain restrictions on bore shape that were laid down have since proved to be not merely desirable for musical usefulness, but actually necessary if the vibrations in the instrument are to be sustained at all by means of the reed system.

B. The second step was somewhat more difficult to achieve, although the goal was quite clear: a formulation of the dynamical behavior of a pipe provided with a set of side holes as in woodwind instruments. Mathematical techniques were developed for the analysis of such a system, and preliminary experimental verification was made. The mathematical results were published in a long article: Jour. Acoust. Soc. Am. - 32, 1591 (1960). An invited paper on the subject was also presented at the fall, 1959, meeting of the Acoustical Society. As a senior thesis project, William Dent(Case 1960) made some further experiments with waves in a duct with open side holes having variable size and spacing. Publication of all the experimental work was postponed because the agreement was apparently so close between theory and experiment that the limits of validity could only be found with more specialized measuring equipment than was available at the time.

C. The general problem of how the reed system provides a regenerative action supporting the oscillations in musical instruments became, in the course of time, more and more relevant to these other problems, if only to show where its effects could safely be set aside for future study. Certain classical results in the linear theory of regeneration were generalized and made useful for the study of wind instruments; in addition, some new results were also obtained. Much of this work on linear theory was carried out in connection with a course entitled Oscillation and Waves which I have taught from time to time. However, it was quite clear that the actual regenerative mechanism could not be described completely by a purely linear theory. In consequence, an essentially non-linear type of theory was needed.

A general mode of attack on the problem of nonlinear oscillations in wind instruments began to develop after 1959. Even in its embryonic form this theory could clarify a number of phenoma relative to intonation and register changing in woodwinds, as well as certain effects occurring in brass instruments. The complexity and intriguing nature of these developments has led to repeated reformulations as new insights have appeared. Due to the unavoidable complication of the algebra, interpretation is sometimes difficult without resort to computational "experiments". One such was carried out by D. J. Gans as another senior thesis project in 1960. Since that time there have been several returns to the subject as new information on musical phenomena turned up. While a considerable fraction of this study can now be put in publishable form, it is clear that a great deal more remains for investigation. There are many practical implications here for the design of wind instruments, and there are also theoretical and practical uses in technological fields far from music.

D. A book on musical physics (primarily for high school students and musically interested laymen) was written at the request of the Physical Science Study Committee. This book was published under the title Horns, Strings and Harmony (Doubleday, 1960). While ostensibly written at an elementary level, this book was in fact an attempt to make a careful reformulation of the physical basis of musical instruments, with close attention paid to the actual physics involved. In other words the book was intended as a surface view of, and outline for, a much deeper analysis.

The success of this literary undertaking has been gratifying upon several grounds: It has had a good sale, over 50,000 copies. Besides its appeal to the audience for whom it was commissioned, the book has also made a growing place for inself as a text for music students at several universities. While many things in the book were set down with some trepidation as being heretical, both in physics and in music, a very gratifying correspondence has grown up with musicians and with scientists who seem to find that the book has information and stimulus to offer them. Thirdly, and perhaps most particularly relevant to the present proposal, is the fact that the book's more technical side is quite visible to the reader who is ready for it. Readers have frequently made remarks like the following: "I can see where all the equations are that you left out, and their general shape. Why don't you write the book again with them all left in?"

One result of the writing of this book has been to increase my own interest in the acoustical behavior of the brass instruments, and also in that of the violin family. A vigorous correspondence with various people with similar interests has grown up particularly with Carleen Hutchins and the group associated with her which is so successfully carrying on the research with violins that was started many years ago by Frederick Saunders of Harvard.

E. More recent efforts along the line of musical acoustics are the following:

a) A new approach to the problem of playing difficult high notes on the brass instruments. This arose chiefly out of a correspondence with W. T.

Cardwell, and also abetted by exchanges with E. L. Kent of C. G. Conn Ltd. and R. D. Olson of F. E. Olds and Son Inc. A preliminary analysis suggested changes in the design of trumpet bells for use in high music. These changes were later correlated with the design of certain 18th century instruments which were used for such music. Some experimental work has been done, but more is needed before an account can be published.

b) A computational method has been devised by means of which bore corrections can be calculated to remove the otherwise inevitable residual tuning errors of a wind instrument. The technique involved is borrowed from that used to extract photonuclear cross section curves from yield data taken with a betatron. S. Machlup of Western Reserve University collaborated in an attempt to write a computor program for this procedure. A minor hitch developed, and was not resolved before Professor Machlup left Cleveland on a year's leave of absence. A second attempt will be made in the near future.

c) A detailed analysis of the flute has been worked on during the past two years, partly in collaboration with J. W. French. A preliminary account of this work was presented at the May 1962 meeting of the Acoustical Society. After a year's lapse, the flute has been taken up again, and two papers are now in active preparation.

d) The existence of certain variable discrepancies in the tuning of flutes, together with some anomalous data on horn resonances provided by E. L. Kent of C. G. Conn led to the realization that non-uniform temperature distributions can lead to changes in the effective <u>shape</u> of a wind instrument bore, and so to changes in the relative tuning of the various registers of the instrument. A theory was constructed and verified experimentally for flutes, clarinets, and oboes. A preliminary account of this research was given at the

November 1962 meeting of the Acoustical Society at Ann Arbor - Jour. Acoust. Soc. of Am. 35, 1901 (1963). A more general discussion of the needs and methods for cooperation of musicians and scientists in musical acousts was given at this same meeting as the keynote address for an all-day Symposium on Musical Acousts, sponsored jointly by the Acoustical Society and the University of Michigan School of Music.

e) Over the years, a desultory but very stimulating consulting activity with the Schantz Organ Company has given me some experience in architectural acoustics and has clarified many points concerning the behavior of musical systems, particularly in regard to nonlinear phenomena occurring in reed pipes. A recent outgrowth of this activity has been a calculation of the contribution of the pipe organ to the total sound absorption of an auditorium. The effect is reasonably large, and the formulas turn out to be simple enough for routine computation, when use is made of the pipe-scaling uniformities which are a part of organ design. Experimental checks will be made at a new chapel in which a Schantz organ is to be installed this spring.

III Present Status

During the spring of 1963 it became clear that it would be worth while to make a definite shift of research emphasis in the direction of major occupation with musical acoustics. After a period of thinking about the suitability of the Case environment for such activities, and about the minimum needs for equipment, the subject was broached to colleagues and to the Chairman of the Physics Department. The reaction was unanimously favorable, and a total of about $2500 was made available to pay for special equipment, to get things started.

The purchase of a Stroboconn for frequency measurement, a power amplifier and driver system, and a pair of condenser microphones formed the nucleus of the initial equipment purchase. There was a good tape recorder, a sound level meter and a white noise generator already available, as a reflection of the long standing interests of members of the department, Professors R. S. Shankland, L. L. Foldy, and F. Reines in particular. Other,more specialized equipment was designed and built, and certain unused equipment from around the laboratory has been modified and pressed into service.

At present there are good facilities for the excitation and accurate measurement of single air resonance frequencies, and for the measurement of the various mechanical dimensions of a wind instrument bore. Good spectral analyses are not possible, nor are there any facilities for the measurements of many of the various sorts of transient phenomena which are of musical interest.

Certain measurements on flutes have been made with the new equipment, all of the research on thermal effects in wind instruments, and almost all of that concerned with the stringed instruments. Current activities include a careful study of various acoustical parameters of woodwinds (side-hole impedances, corrections for pad elasticity, damping factors, etc.) that are needed for quantitative calculations based on fundamental theory. An exploration is also in progress on the possible uses of the time-domain reflectometry of acoustical pulses as a means for studying the dispersion of waves in wind instruments, and as a basis for calculating the transient behavior of their regenerative reed systems. These last two projects are being carried on with the help of two physics students who were among those selected by the department for the privilege of doing a senior thesis.

IV Plans for the Future

A. January 1964 - June 1964

Plans for the immediate future may be summarized briefly: to complete as much as possible of the nearly-finished earlier work, and to provide a basis for longer-term studies.

During the next six months it is anticipated that the work on the flute can be completed, as well as the study of acoustical parameters. Pipe-damping observations which are required for a test of the pipe-organ absorption analysis, and experiments on certain small effects arising from transient thermal perturbances in woodwind bores will also be carried out when suitable equipment becomes available. A certain (relatively small) amount of effort will also be invested in the measurement of air and body resonances of stringed instruments provided by Mrs. Hutchins. This continues present practice, and will not require additional instrumentation, beyond a few items that she will lend.

B. June 1964 - June 1965

During the calendar year beginning in June 1964 I will serve as visiting professor in the physics department of the Indian Institute of Technology at Kanpur, India, representing Case Institute. During this time, it is anticipated that the opportunities for acoustical research will be limited by the press of other activities: However, certain selected items of equipment will be taken along for use in India. In any event there are two aspects to the situation which will prevent this period from being completely barren of acoustical productivity:

a) The Institute at Kanpur is initiating a research program in low-speed aerogynamics, for which the early steps have been taken by Professor Robert Halfman of M.I.T. (among others) and which will make its major beginnings under the guidance of Professor David Hazen of Princeton during 1964. Professor Hazen intends to set up promptly a number of small-scale research projects involving the stability of air jets, a matter that is also of great interest to anyone concerned with the acoustics of flutes and organ pipes. In informal conversation it appears that Professor Hazen and I could collaborate with considerable mutual benefit. Such collaboration would be welcomed by the Institute Director since it is his expressed desire that visiting faculty members set an example of interdepartmental cooperation in research and in teaching on the Kanpur campus.

b) The tradition of hand-craftsmanship which persists in India couples with the very low pay scale for artisans to make India an ideal place to go for the construction of special musical pipes and resonators. It should be remarked parenthetically that Indian-made brass instruments are at present being sold competitively in the United States at a good profit. In November of 1961 I spent a month in India to assist in the planning for the United States collaboration at Kanpur, and took the opportunity to have a pair of special trumpet bells made to order at a cost of about $10 apiece. A band instrument manufacturer has estimated that the cost of these bells would have been several hundred dollars if made in an Americal model shop. There are a number of special shapes of bore which I expect to have made in India.

C. <u>June 1965 - June 1966</u>

It is more difficult to predict in detail the nature of the program in the year following the India trip. There will undoubtedly be need for more equipment, although its detailed nature can only be partly foreseen. However, there is a clear anticipation that one or more graduate students or others will become affiliated with the project, all of whom will need at least partial support in the way of stipends in addition to the expenses of their research.

The year ending in September 1965 can be usefully employed in making contact with suitable people for joining the project, people who have at least "good amateur" status in one part, and professional abilities in the other part of the dual field which is musical acoustics. It is only such people who can hope to communicate for mutual benefit with full time practitioners of music and of science, and so also have a reasonable chance of making worthwhile syntheses of their own.

During the past two years at least seven well-quilified individuals from all over the United States have made serious inquiries about the possibilities for doing research at Case in musical acoustics. Most of these were prospective graduate students interested in physics degrees, but two were scientifically interested members of university music departments, one of whom wished to spend a sabbatical year at Case, and the other was seeking an opportunity for post-doctoral study. A particularly favorable aspect of these expressions of interest was that they came entirely unsolicited, since no public accouncement has as yet been made about the possibilities for such activities at Case.