ACOUSTICS OF WIND MUSICAL INSTRUMENTS

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Introduction

This paper has two goals: first, a brief description of the physics of wind-driven musical instruments; second, a report on a very recent study of one feature of the *shehnai* and its Western counterpart, the oboe, which illustrates nicely the contrast in the two societies' criteria for acceptable musical instruments. The description of principles which underlie the action of wind instruments is included in order to indicate some lines along which the study of indigenous instruments might progress. The work I have done recently with the *shehnai* while providing a quantitative description of the shehnai's "flexibility" (indicated by the fact that a relatively broad range of pitches can be played with any given fingering), reveals an aspect of musical instruments that can be studied rather easily, can be significant "musically" as well as technically, and that has not received much prior attention.

Briefly, the result is that the *shehnai* has a pitch flexibility which is twice to thrice that of the oboe, its Western physical counterpart. I suspect, but have not yet demonstrated, that the difference is predominantly due to the differences in the construction of the reeds used on the two instruments. This physical difference reflects the selection of properties of the instruments on the basis of aesthetic requirements: flexibility in pitch is a fundamental necessity in Indian melodic instruments; in Western music, accuracy of pitch and an optimum tone quality are the primary concerns.

Wind-driven Musical Instruments

We have a saying that the oboe is "ill wind that nobody blows good". Although such statements may be very revealing of a player's (or listener's) attitude towards an instrument, they do not advance our understanding of the features of the instrument which led to the formation of that attitude — nor of the characteristics which differentiate between instruments. The physics of musical instruments has been the subject of considerable enlightened (scientific) speculation for a long time. The broad outline has been established clearly; wherever funding is available, work is still being done on the details.

Wind instruments are rather complex machines. The scientist's task is complicated by the fact that any instrument is the result of centuries of development through trial and error. As a result, it is quite often difficult to separate an instrument into components which can be studied individually; when this is possible, some of the parts present problems which are extremely difficult even with the mathematical tools presently available. Experimentation is made difficult by the small size of interesting regions and by the use of the player's breath as the ultimate source of energy.

Almost every text-book in acoustics contains a chapter on musical instruments. Therefore only a brief sketch of the well-established factors will be presented here. There are three primary elements in any wind instrument: an excitation mechanism, the player's connection with the instrument; the horn, the body of the instrument which may be viewed as a resonant system or as a filter acting on the output of the exciter; and a radiator of the resulting sound to the environment.

The most common excitation mechanisms are the jet and edge, used in the flute and whistle, vibrating reeds (single and double), and a cup-like mouthpiece, used in brass instruments. None of these mechanisms is easily studied analytically; for example, edge tones seem to be due to formation of eddies; reeds are not made in (mathematically) convenient shapes, nor are their thicknesses and tensions uniform; the cup mouth-piece is relatively simple, but the vibration of the player's lips seems to give rise to a non-linear process. Of course, for each exciter, the presence of the player on one side and the horn on the other imposes grave restrictions on its actions.

The horn parts of wind instruments are of two kinds: those with holes in the side and those with valves for adding lengths of tubing to alter the fundamental frequency. This aspect of wind instruments has been thoroughly studied. In the instruments with side holes, most of the radiation takes place through open holes. On the brass instruments, however, the radiation is all from the end of the tube; thus the brass instruments are fitted with flared bells which add to their efficiency as radiators. One further parameter, the shape of the horn, distinguishes the appearance (and also the tone quality) of wind instruments. There are three basic shapes which are variations of tube area as a function of distance along the axis: cylindrical—flute, clarinet, trumpet; conical—*shehnai*, oboe, saxophone, cornet; exponential—French horn.

The wind instruments used today present a variety of combinations of the characteristics listed above. It is interesting to look at several of these in order to relate the differences in tone quality to the way the components of the instruments vary. The grosser differences are due to the use of different exciters. The *shehnai*, saxophone, cornet, and a noisemaker prominent in Jaipur's Moharrum celebrations all have conical horn bodies; the *shehnai* has a double reed, the saxophone a single reed, the cornet a cup-mouthpiece, and the noisemaker a "beating reed" — a tongue which flaps in a hole just slightly larger than itself. Each instrument sounds unmistakably different from the others. The flute, clarinet, and trumpet all have cylindrical bodies, but their respective excitation mechanisms —

jet and edge, single reed, and cup-mouthpiece — are largely responsible for the differences in the sound of these instruments.

The differences associated with variations in the shape of the horn are more subtle than those listed above. The only groups of instruments in which the full range of shapes has been used is the Western brass instruments — the trumpet is cylindrical, its sound is more brilliant than that of the cornet, which is conical. The French horn has an exponential horn, which gives it a greater range of possible qualities, and also a flexibility which is dangerously close to instability. We can see the difference made in the *shehnai* by the presence of the flared bell by removing the bell. The difference can be heard, but statements about it must be deferred until objective measurements have been made. There is another factor which can cause noticeable differences in the tones of similar instruments. We shall see later some evidence of the contrasting qualities of the *shehnai* and the oboe, both of which use double reeds and conical horns. I strongly suspect that the difference in construction of the reeds for the two instruments is primarily responsible for the contrast.

Thus far, we have seen only qualitative descriptions of the possible variations in tone quality of wind instruments. These descriptive observations may be quantified by spectral analysis of tones from the several instruments. Such work has been done on Western instruments throughout this century; the methods and equipment have benefitted greatly from the electronics explosion.

While spectral information is of great use to those who wish to catalogue differences or to reproduce the sounds of an instrument by electronic means, it is of limited usefulness in describing the physics of the instruments. Further, it is of no use as a presecriptive device for improvements in present instruments or for the design of new instruments. The development of electronic circuit theory has led to a useful analytic method which is particularly appropriate for the study of the horn section of an instrument. It is also possible in principle to deal with the effect of the excitation device as well, although this has not been done with proper thoroughness.

The fundamental conceptual quantity is the impedance: in circuit theory the ratio between voltage and current; in acoustics, the ratio of pressure to volume velocity. Parts of the air column in a wind instrument are treated as "lumped" parameters. Analogies are drawn between these features and corresponding electrical quantities, thus making it possible to use the well-developed techniques of circuit theory to descibe the action of the acoustical system. The relevant quantities are the acoustic mass of a slug of air in an orifice (corresponding to an electrical inductance), the compliance — inverse of stiffness — of the air in a closed volume (corresponding to a capacitance); and a resistance, which in musical acoustics relates to the loss of energy of the instrument due to radiation.

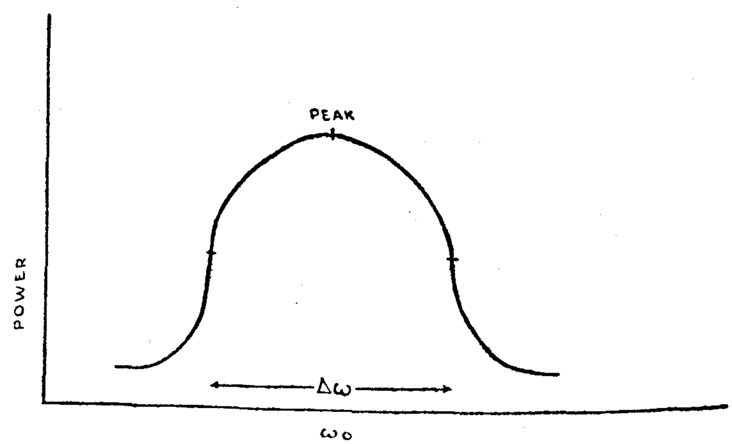
The simplest case relevant to musical instruments is a cylindrical tube, of length l and area S. The impedance at the throat end is

where ρc is the characteristic impedance of the medium (air) inside the tube, k is the wave number $2\pi f/c$ (f is the frequency), and Z_l is the impedance at the end of the tube. Z_1 represents the "outside world" as seen in "lumped" form by the instrument. The combined system has a number of resonance frequencies, which occur when the imaginary part of Z_0 vanishes. It happens that the real part of the impedance, responsible for radiation, has a maximum at each of these resonance frequencies. This sort of calculation is treated in most acoustics texts. It is also possible to treat conical and exponential horns in the same manner. The variations of the heights of the maxima in the resistance curves for each type of horn are closely related to the tone quality expected from the instrument when several resonant modes are excited.*

It is also possible in principle to include in this analysis the impedance of the exciter, although this has so far been done only in a crude manner. In most instruments, this impedance makes a significant contribution to the impedance of the instrument-system — hence to the resonance frequency. Further, the player's reaction to the instrument includes (is highly colored by) the impedance of the excitation mechanism. Thus a closer study of this portion of the system seems to be in order. As I have said the problems which arise are not easily solved.

A recent comparison of the Shehnai and Oboe

One feature of resonant devices which has not received much attention in musical instrument acoustics in the "tuning parameter", Q, a widely used quantity in circuit theory and mechanical systems. Among other things, the Q of a circuit gives a measure of the width (in frequency) of a resonance peak in the output from the system. For an acoustic device treated as a set of lumped elements, $Q = \frac{w_0 M}{r}$ where w_0 is the resonance frequency in radians per second. For large Q, we may also use the description that $Q = \frac{w_0}{\Delta w}$, where Δw is the separation of the two frequencies, above and below the resonance peak, at which the output power has fallen to half the peak value:



*The interested reader is refferred to e.g., H.F. Olson's *Musical Engineering*. pp. 83-99, for a more complete discussion.
(McGraw-Hill Book Co., Inc. New York, 1952).

In the musical context, the size of the Q factor is related to the ease with which an instrument may be made to play at a frequency other than a resonance of the system. (Of the wind instruments, only the trombone is truly capable of playing at continuously varying frequencies over an extended range, but this is due to its movable slide, not to Q). As a player of several Western instruments I was struck, when I began to learn to play the *shehnai*, by the great ease with which it could be made to play pitches which on a Western instrument would have required a change of fingering. The oboe, on the other hand is considered so inflexible that it is used as the tuning standard for the orchestra.

When the invitation came to participate in this Seminar, I decided that this effect was one that could be studied with a minimum of equipment, opened a neglected area of investigation, and in the case of the *shehnai* and oboe, involved socio-cultural attitudes towards music in the explanation of the origins of the contrast between the actions of the two instruments.

The work I have begun is directed towards measuring the Q of the *shehnai*-as-acoustical-system. At a more leisurely time, I shall attempt to obtain an expression for Q from the expression for the impedance. In the experimental investigation, there are two deviations from the conditions under which Q may be obtained as $\frac{w_o}{\Delta w}$. First, this form is valid only for large values of Q; those found for the *shehnai* are quite small. Second, Δw is measured from the half-power points for constant driving force; keeping the breath pressure constant while attempting to play the highest and lowest notes with a given fingering is virtually impossible.

With these qualifications, then, the investigation proceeded as follows. For each fingering of the *shehnai*, the highest and lowest pitch attainable by variations in lip presssure on the reed, etc., were played. The frequencies were measured by comparison with a sine-wave generator. The frequency range thus covered was approximately 200 to 1,000 cycles per second. This procedure was followed through five trials on each of four reeds. Fourteen "notes", almost two octaves, were used (thus including the Q of the instrument when played so that the second harmonic is the perceived pitch). Simultaneously, my brother, a student oboist in the United States, performed the same experiment for a few notes of the oboe.

The average of the highest and lowest frequencies for each fingering was taken as w_o for the calculatin of Q. This was especially necessary for the *shehnai* because of the difficulty in finding the "peak" of the response (See Figure). The width, Δw, ranges from 30 cycles per second to 250 cycles per second, depending on the length of the active air column.

There are several qualitative features of the study which warrant mention. Three of the *shehnai* reeds were new when the investigation started. It was interesting to note the changes in the Q as they became 'broken in' through use. There is a general downward trend in the Q values for these reeds as a function of playing use. One of these new reeds has felt consistently stiffer and less responsive than the others; its Q values are generally higher. There is considerable variation in the Q values for the one "old " reed, which is usually satisfactory in its performance. Fluctuations from trial to trial merely indicate that the conditions of wetness, reed, opening shape, and level of player fatigue were not the same in each trial. For this reason, there is safety only in large numbers of trials, and in speaking of averages over such ensembles.

The full Q data for the "old" reed and the "new' reed which presently performs best are presented in Table I. Table II contains the average values of Q for each reed. The averages over the set excluding the first trial for each reed are also included. This is done because, in a sense, one must develop an expertise at forcing the instrument to play at the extremes of the frequence "band" for each fingering. Finally, the average Q for each note over the entire set of reeds (including and excluding the first trial) are included. Table III contains the Q values for certain notes of the oboe.

It is noteworthy that the Q's for the second harmonics are slightly lower than for the first harmonics. The rise in Q for the highest note is related to the fact that it is difficult to make the note speak at all. The high Q for the lowest note and its octave is probably due to the increased importance of the radiation impedance which acts at the end of the horn for these notes.

Conclusion

The fact that the Q values for the oboe are larger than for the *shehnai* by roughly a factor of three illustrates nicely a contrast in the demands on musical instruments made by Indian and Western musical aesthetics: the *shehnai* has the flexibility which is so necessary for playing the music properly, while the oboe has the accuracy of tuning and refinement of tone quality desired by Western listeners.

My suspicion that the reeds are largely responsible for the difference in Q of the two instrument is supported by the variation of the Q values as the new reeds were broken in. In fact, it is quite likely that an optimum set of values for Q may be formed, which would furnish an indication of the quality (or at least utility) of a reed.

There are several portions of this work which demand further study, most notably the development of an expression for the reed's impedance. In addition, a spectral analysis of *shehnai* tones would be of interest. These questions pose a stimulating challenge to further investigations.

TABLE I

Values of Q for Two Reeds

Note / Trial	Old I	II	III	IV	V	New Reed # 3 I	II	III	IV	V
C	7.29	5.70	7.34	6.51	6.01	6.55	6.46	4.55	2.86	3.20
D	7.74	4.33	4.40	4.78	3.34	5.74	4.50	3.51	2.96	3.23
E	5.78	2.84	3.59	3.28	2.94	4.55	3.36	3.37	2.83	2.67
F	5.03	3.02	3.04	3.34	2.94	3.66	3.23	3.00	2.66	2.73
G	3.94	2.74	2.82	2.80	2.72	3.93	2.97	2.88	2.64	2.69
A	3.41	2.84	2.72	2.67	2.78	3.47	2.83	2.91	2.40	2.37
B	3.48	2.31	2.65	2.58	1.42	3.01	2.58	2.16	1.87	1.30
C'	3.78	4.22	3.02	3.19	2.86	4.12	2.86	2.96	2.80	2.62
D'	2.81	2.56	2.24	2.39	2.38	2.96	2.93	2.49	2.34	2.30
E'	2.55	2.46	2.25	2.55	2.29	3.26	2.42	2.40	2.52	2.40
F'	2.58	2.74	2.47	2.51	2.37	3.70	2.52	2.57	2.50	2.44
G'	3.21	3.17	3.10	2.87	2.82	3.99	2.97	3.24	2.68	2.80
A'	4.78	3.24	3.64	4.17	2.82	5.71	5.53	4.35	4.57	3.74
B'	6.85	6.54	6.34	7.55	7.25	—	9.88	7.48	10.60	8.75

TABLE II

Average Values of Q

(Upper entry: trials)
(Lower entry: excluding first trials)

Note	Reed Old	New 1	2	3	All
C	6.57 6.39	6.55 —	7.13 6.87	4.72 4.27	6.13 5.99
D	4.92 4.21	5.33 4.63	5.31 4.80	3.99 3.55	4.86 4.28
E	3.68 3.14	4.06 3.81	4.52 4.02	3.86 3.06	3.89 3.54
F	3.48 3.09	3.36 3.12	3.62 3.53	3.06 2.91	3.38 3.09
G	3.00 2.77	2.96 2.87	3.62 3.49	3.02 2.80	3.16 2.98
A	2.88 2.75	2.83 2.68	3.14 3.01	2.80 2.63	2.92 2.77
B	2.48 2.44	2.56 2.36	2.83 2.66	2.18 1.98	2.51 2.31
C'	3.41 3.32	— 3.27	3.86 3.55	3.07 2.81	3.42 3.24
D'	2.48 2.39	— 2.46	2.79 2.67	2.60 2.52	2.59 2.50
E'	2.44 —	2.66 2.43	2.77 2.59	2.66 2.51	2.63 2.49
F'	2.53 —	2.61 2.48	2.75 2.59	2.71 2.46	2.64 2.51
G'	3.03 2.99	— 3.03	3.26 3.14	3.14 2.92	3.12 3.02
A'	3.73 3.47	4.20 —	4.35 4.21	4.78 4.55	4.22 4.11
B'	6.91 —	7.07 —	7.00 6.42	9.13 —	6.97 6.14

TABLE III

Values of Q for Certain Notes of the Oboe

Note	Q
D	13.80
G	8.95
A	9.80
B	6.90
E'	7.68
G'	5.78