

Physics and Wind Instruments

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(Reprinted from the *Double Reed News* of the *BDRS*. No. 51, pp. 29-31. Used with permission. — ED).

It is a popular belief that there is a high correlation between interest or ability in music on the one hand and in physics or mathematics on the other. That this is a fallacy has been shown by the statistical studies of G Révész (1953). It probably arises from the publicity accorded to the musical exploits of those famous scientists who are found to be proficient instrumentalists (such as Heisenberg and Max Born on the piano, Einstein on the violin and D.C. Miller on the flute). The mere fact of the combination having such publicity value suggests that it is the exception rather than the rule.

Of course it is true that many mathematicians and physicists have been attracted by the prospect of grasping and systematizing the elements of order in music, such as those to be found in scales, harmony and form. The famous American mathematician, G.D. Birkhoff, has even attempted to devise a means of measuring the aesthetic value of a musical work by a scale based on the elements of order. (Birkhoff, 1950). He applies this scale to the famous *Ode to Joy* theme of Beethoven's ninth symphony and succeeds in giving it a high score by ignoring just those elements of rhythmic irregularity and anticipation which raise it above the level of a beginner's conventional exercise.

Curiously enough, the popular belief does not apply to the reverse direction: there is little suspicion that professional musicians excel in physics or mathematics - and certainly even less evidence. This is a pity, because basically the functioning of all musical instruments depends upon these subjects. Musicians tend to have scant understanding of the physics of their instruments; even reputable authorities come out with astonishing mis-statements and continually repeat ancient superstitions; whilst physicists, on the other hand, have the comfortable feeling that all such matters have been settled centuries ago and that all that matters is being up-to-date, studying quarks, gravitational waves of tachyons, which are either non-existent, as yet undiscovered or logically absurd.

(A characteristic of modern physics is that it is adept - like even Course I textbooks - at solving the artificial problems it sets itself; but present it with a problem from real, everyday life, and it covers its confusion at being unable to find an answer by declaring that it is trivial, old-fashioned or non-existent! How is one to view this instruction from an examination handbook: "The syllabus should contain material from the frontiers of modern physics. Illustrations should be drawn from everyday life?" A greater contradiction could scarcely be imagined.)

Numerous examples could be given of physical "howlers" committed by musicians writing on instruments; and of naive and over-simplified treatments given by physicists which are quite inadequate to account for the observed instrumental behavior. One sometimes wonders whether the physicist has ever seen the instrument he is discussing, as when Morse (1948) states: "A flute is also an open tube, set into oscillation by a jet of air which the player blows across the open end at $x = 0$... The inner bore of the actual flute is not a uniform tube, but is conical in shape," or Richardson (1953) includes the clavichord with the harp and banjo under plucked string instruments and describes the recorder studied by von Luepcke (1940) as the orchestral flute.

Here we can do no more than hint briefly at some of the discrepancies in the usual treatments given of the physics of wind instruments.

Taking first the woodwinds: the basic physics is simple. The air in a cylindrical pipe open at both ends can vibrate longitudinally in a number of "normal modes", each having a velocity antinode, or region of maximum movement, at each open end. Writing the arrangement of antinodes and nodes schematically, the various possible modes of vibration can be represented as ANA, ANANA, ANANANA, etc. and it is clear that the successive wavelengths are 2, 2/2, 2/3, times the length of the pipe, and the frequencies in the ratios 1, 2, 3, etc. A correction is necessitated by the fact that the effective antinodes are not exactly at the ends of the pipe, but slightly outside it and the amount of this correction varies somewhat with frequency.

This is the basic theory of the flute and here most physicists are content to leave it. In the real flute the complications arise that, whilst the far end is indisputably open, the near end or embouchure is not an end, but a side hole partially covered by the lips and forming part of an elongated, tapering "head-joint". No matter - the celebrated Belgian organ-building Cavaillé-Coll, has given an empirical formula taking care of this.

It remains to set the air in the flute into vibration in one or other of its normal modes. How is this done? The flautist directs a narrow jet of air at the edge of the mouth-hole. This is supposed to generate an "edge-tone". Such edge-tones are well-known. When a thin stream of air impinges on a sharp edge, it breaks up into vortices which are shed alternately on either side of the edge. The frequency of these vortices can be simply expressed in terms of the lip-edge distance and the speed of the air-stream. In the conventional theory of the flute it is assumed that the vortices which are shed inside the tube set up the resonant vibrations of the air column. Unfortunately, it does not seem to have been noticed, except by Bouasse (1929, 1930) that the frequencies of the latter are considerably lower than the expected edge-tone frequencies. The true edge-tone frequencies may be heard by underblowing the flute (or recorder), when the note produced will suddenly jump up an octave or twelfth, etc., in complete contradiction to classical physical theory, which requires overblowing in order to elicit higher frequency modes of vibration. (The work of Bouasse has been followed up and confirmed by Mercer (1954) and Benade (1965). See also Coltman (1966, 1968), who partially disagrees.)

So far we have only dealt with the (approximately) harmonic series of frequencies emitted by the column as a whole. What of the intermediate notes? It is well known that, by successively opening holes from the bottom upwards, the effective length of the vibrating air-column may be shortened and the frequency raised. After centuries of trial and error, and the quasi-theoretical efforts of Boehm, positions and sizes for the side holes have been found which are reasonably adequate. Physicists have attempted calculations of the natural frequencies of tubes with side-holes, using electrical analogies and formulae for iterated impedances, completely overlooking the fact that the acoustic system contains features such as viscosity, thermal conductivity and vorticity which have no analogue in the idealized

electrical circuit containing pure inductance, resistance and capacitance. Needless to say, the physicists' formulae give results to no better than a few percent, which would be quite unacceptable to a sensitive ear, requiring an accuracy of less than 1/4%. It is thus rather amusing to read the complacent remarks of Richardson(1940): "A feature of the wood-wind which, until recently was decided by empirical methods has now been rationalized by the physicist. We refer to the location of the side holes which determine the scale which the instrument will play ... Formerly it was not possible to calculate the effect of uncovered holes beyond the first open one. The theory of acoustic impedance now permits of the calculation of the position and size of the side holes in such cases, corresponding to a predetermined arrangement of fingering. This can be done in advance of the construction of the instrument, so that one does not need to waste good wood as in the old trial-and-error methods." One need only add that it is fortunate that so far no wind instruments have been made entirely according to the physicists' design, as the wastage of wood would have been complete. (A more realistic and honest view is expressed by Backus (1963a): "Musical instruments have developed into their present forms through empirical processes in which acoustical theory has played a negligible role".)

A great deal of nonsense is talked by musicians about the material of which woodwind instruments are made. The first (and only) essential is that it should be rigid and smooth. The sound comes from the contained air and not the tube itself. Unfortunately, when comparing the sounds of, for example wooden and metal flutes, musicians suffer from a great deal of imagination (just as, in other respects, physicists suffer from a great lack of imagination!) By using a sufficiently thin-walled tube, one can, in fact, get it to participate in the vibration - with disastrous consequences: distressing buzzes and rattles, dependent upon the note played and on the exact placing of the fingers on the tube.

The other (mainly) cylindrical pipe in common orchestral use is the clarinet. Here the vibration generator is a beating reed, i.e., a slip of cane which alternately closes and opens the aperture in the mouthpiece. The variation of pressure in the tube just inside the reed is at a maximum, and the reed end of the pipe thus behaves, in physical terms, as a pressure antinode, or velocity node. (Approximately - it

should be noted that none of the “nodes” in wind instruments can be true nodes in the physical sense since, if they were, no energy could pass them and the instrument would be inaudible). The possible schemes for the air vibrations in a clarinet are thus NA, NANA, NANANA ... corresponding to wavelengths of 4, 4/3, 4/5 ... times the length of the tube, and frequencies in the ratios 1, 3, 4, etc. By overblowing the clarinet only the odd harmonics should be elicited, a prediction which is fairly accurately borne out by experiment. Admirable confusion reigns as to the mode of action of the clarinet reed. Ghosh (1938) claims to have shown that the reed never closes the mouthpiece orifice completely. Aschhoff (1936) has produced a remarkable research in which the overblown frequencies produced by a mechanically blown clarinet appear to have no relation to the fingering or blowing pressure, but consist of a series of arbitrary high-pitched squeals. Such squeaks (which Aschhoff elicited by reducing the lip pressure) are only too well known to beginning clarinetists, and would certainly lead to the immediate eviction of his instrument from any orchestra in which it attempted to appear. Morse (1948) has given a theory of the clarinet which involves an elaborate motion of the reed in complete contradiction with anything that has ever been observed experimentally. Backus (1963) has finally (literally) thrown some light on the subject by the simple expedient of directing a light-beam through the length of the clarinet on to a photo-multiplier tube.

Reed functioning is still less understood for the double-reed instruments, having conical tubes, with the reed at the narrow, or throat, end. The physical theory of spherical waves in conical pipes (Morse 1948) shows that there is effectively a velocity antinode, not at the reed, but at the apex of the cone produced. Calculations based on this theory give approximately the frequencies observed, but leave unexplained the remarkable dependence of the exact frequency on the precise dimensions and characteristics of the reed. To add to the confusion, use of a slightly different reed may flatten some notes considerably and leave others unchanged, whilst the opening of an auxiliary finger-hole will on one bassoon sharpen the note sounded and flatten it on another of ostensibly the same construction. Reeds and their vagaries are the nightmare of the oboist, clarinetist and bassoonist, as is illustrated by the attempted suicide of a

prominent British oboist after the death of his usual reed maker, when he felt that he would never again be able to perform satisfactorily! Countless micrometer measurements of reeds have been made by many instrumentalists, especially in the USA (Spencer 1958), but have contributed little to our understanding, in the absence of any theory or other means of systematizing them. In the same way, the attempted use of plastics and other materials for reed-making has generally failed, and it remains a mystery why the best reed material should be the particular brand of *arundo donax* grown in the south of France. Any physicist who could solve this problem would put out of their misery many thousands of wind-players and would perhaps do an even greater service to humanity than he could by discovering the umpteenth excited state of the omega minus hyperon.

Coming to the brass instruments, we find the amusing situation that the physical theory taught, where it is taught at all, is patently inapplicable. Here the lips of the player function as the reed, and a cylindrical brass instrument should thus sound only the odd harmonics and a conical one the full harmonic series. Unfortunately for the theory none of the brass instruments is either cylindrical or conical. All are necessarily cylindrical for part of their length (the valves of trumpet, horn and tuba and the trombone slide) and clearly conical elsewhere. The overtones thus fall somewhere between a complete series and an odd series starting one octave lower. Fortunately for our ears, the musician (with his lips) and the instrument maker (by tricks of design) are able to pull them approximately into tune, and we are able to listen to the brass section with a satisfaction for which most physicists can give no reasonable explanation. (See however, the paperback “Horns, Strings, and Harmony” by Arthur H. Benade for an excellent introduction to the real physics of the brass instruments, as well as a penetrating discussion of the reeds).

Lest it be thought that this article is entirely devoted to parading the physicist’s ineptitude in explaining the functioning of musical instruments, I close with an illustration of the reverse error: the farcical blunders into which musicians can be led by an uninformed and implicit belief in the latest gimmicks of physics. In the newsletter *To the World’s Bassoonists* (March, 1970) it is reported as follows: “**Milan Turkovic** of the Vienna Symphony reports that several wind players of his orchestra have applied to technicians of the Austrian Atomic

Research Centre to have brass instrument mouthpieces and reeds and reed cane irradiated with atomic particles. The hope in irradiating the cane is to make the reeds last longer. The brass mouthpieces have been improved in flexibility and response, according to Mr. Turkovic ... If properly irradiated, the mouthpieces should gain in flexibility and/or malleability - properties desirable for efficient vibration."

On that note let us leave this history of misunderstandings, accidents and some real progress. ❖

From "Impulse", Vol. 1, 1970 - Journal of Science Students' Council, University of Cape Town, South Africa.

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