THE FLUTE AND FLUTE-PLAYING

IN ACOUSTICAL, TECHNICAL, AND ARTISTIC ASPECTS

BY

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PART I—THE FLUTE

UPON THE SYSTEM OF

THEOBALD BOEHM

OF MUNICH

I. INTRODUCTION

It is now more than sixty years since I first began to play upon a flute of my own manufacture. [In 1810, "at the age of 16 years he made for himself an instrument patterned after one with 4 keys, loaned to him by a friend. Then he began to blow the flute with gleeful enthusiasm in all his spare time, not especially to the delight of his friends and neighbors."—*Zur Erinnerung an Theobald Boehm.*] I was then a proficient goldsmith and was also skilled in the mechanic arts. I soon endeavored to make essential improvements in the keys, springs, and pads of my flute; notwithstanding all my efforts, equality of tone and perfection of tuning were impossible, because the proper spacing of the tone-holes required too great a spreading of the fingers. In order that the tone-holes might be made of proper size and be placed at the acoustically correct points, it was necessary to devise an entirely new system of fingering. I could not remodel the flute to this extent without sacrificing my facility in playing which had been acquired by twenty year's practice.

Notwithstanding all my success as an artist, the defects of my instrument remained perceptible, and finally I decided in 1832 to construct my ring-keyed flute, upon which I played in London and Paris in the following year, where its advantages were at once recognized by the greatest artists and by *l'Académie des sciences*.

As compared with the old flute, this one was unquestionably much more perfect. The tone-holes, through my new system of fingering, were placed in their acoustically correct positions, and one could play all possible tone combinations clearly and surely. As regards the sounding and the quality of the lower and higher tones there was yet much to be desired; but further improvements could be secured only by a complete change in the bore of the flute tube.

[Figures 1 and 2 are reproduced from Boehm's pamphlet of 1847, *Ueber den Flötenbau und die neuesten Verbesserungen desselben*. Fig. 1 shows his flute on the old system, as made in 1829, while Fig. 2 represents the new Boehm System Flute of 1832.]

Fig. 1. Boehm's Flute
Old System. 1829

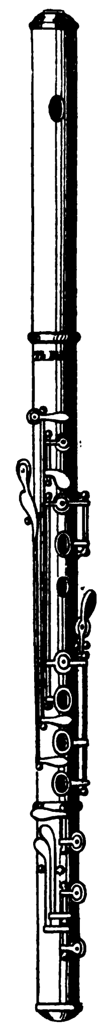

Fig. 2. Boehm's Flute
New System. 1832

The method of boring, with a cylindrical head, and a conical contraction in the lower part, which was first improved by Christopher Denner of Nuremberg (born in 1655, died in 1707), and later by Quantz [1697-1773], Tromlitz [1726-1805] and others, was nevertheless far from being in accordance with acoustical principles, as the places of the finger-holes had been borrowed from the primitive *Schwegel* or *Querpfeife*. This conical bore was in use more than a century and a half, during which no one made improvements in it.

I was never able to understand why, of all wind instruments with tone-holes and conical bore, the flute alone should be blown at its wider end; it seems much more natural that with rising pitch, and shorter length of air column, the diameter should become smaller. I experimented with tubes of various bores but I soon found that, with only empirical experiments, a satisfactory result would be difficult of attainment.

[The flute of 1832, therefore, remained unchanged for fifteen years. Boehm says in his treatise of 1847, mentioned below: "With regard to all the alterations and improvements which have been made in the flute [after 1832], whose value or worthlessness I leave for others to decide, I had no part in them; from the year 1833 to 1846 I gave no time to the manufacture of instruments, being otherwise engaged [in iron work] and for this reason my flute factory was given up eight years ago in 1839."]

I finally called science to my aid, and gave two years [1846-1847] to the study of the principles of acoustics under the excellent guidance of Herr Professor Dr. Carl von Schafhäutl [of the University of Munich]. After making many experiments, as precise as possible, I finished a flute in the latter part of 1847, founded upon scientific principles, for which I received the highest prize at the World's Expositions, in London in 1851, and in Paris in 1855.

Since that time my flutes have come to be played in all the countries of the world, yet my treatise, *"Ueber den Flötenbau und dessen neuesten Verbesserungen"* [Boehm quoted from memory; the actual title is *Ueber den Flötenbau und die neuesten Verbesserungen desselben*], published before that time [in 1847] by B. Schott's Söhne of Mainz, which contains complete explanations of my system with the dimensions and numerical proportions, seems to have had but little influence. Because of the many questions which are being continually asked of me concerning the advantages and management of my flute, it is evident that the acoustical proportions and key mechanism are not sufficiently well understood to enable one to help himself in case of accidental troubles and derangements.

There is need therefore of this work, which will be welcomed by all flute players, in which is given as complete a description as is possible of my flutes, and instructions for handling them, and which also contains instructions upon the art of playing the flute with a pure tone and a good style.

II. THE ACOUSTICAL PROPORTIONS OF THE FLUTE

ALL wind instruments with tone- or finger-holes, whose construction requires very accurate proportions, can be improved only through the investigation of the principles of the good as well as the bad of existing instruments, and through a rational application of the results; the greatest possible perfection will be obtained only when theory and practice go hand in hand. When the calculation of the required data is undertaken, the questions to be first investigated are the dimensions and numerical proportions of the air columns and tone-holes of each separate instrument.

For this purpose I had prepared in 1846 a great number of conical and cylindrical tubes of various dimensions and of many metals and kinds of wood, so that the relative fitness as to pitch, ease of sounding, and quality of tone, could be fundamentally investigated.

The most desirable proportions of the air columns, or the dimensions of bore best suited for bringing out the fundamental tones, at various pitches, were soon found. These experiments show:

1. That the strength, as well as the full, clear quality of the fundamental tones, is proportional to the volume of the air set in vibration.

2. That a more or less important contraction of the upper part of the flute tube, and a shortening or lengthening of this contraction, have an important influence upon the production of the tones and upon the tuning of the octaves.

3. That this contraction must be made in a certain geometrical proportion, which is closely approached by the curve of the parabola.

4. That the formation of the vibration nodes and tone waves is produced most easily and perfectly in a cylindrical flute tube, the length of which is thirty times its diameter; and in which the contraction begins in the upper fourth part of the length of the tube, continuing to the cork where the diameter is reduced one tenth part.

Since the dimensions most suitable for the formation of the fundamental tones correspond closely to those of theory, a flute of these dimensions, the length of the air column being 606 millimeters and its diameter 20 millimeters, having a compass of about two octaves, would certainly be perfect as regards a full, pure tone, and ease of sounding. But in order to extend the compass to three full octaves as now required [in flute music], I was obliged, for the sake of freedom in the upper tones, to reduce the diameter to 19 millimeters and thereby again to injure to some extent the beauty of the tones of the first two octaves.

[In a letter written in 1867 Boehm says: "I have made several flutes with a bore 20 millimeters in diameter, therefore one millimeter wider than usual; the first and second octaves were better, but of course the third octave was not so good. I could, indeed, still play up to C_6, but from $F_5\sharp$ upwards the notes were sounded with difficulty, and if my lip did not happen to be in good order, I could not sound the higher notes *piano* at all. The flute, whether in the orchestra or in solo playing, is treated as the next highest instrument after the piccolo; modern composers do not hesitate to write for it up to C_6; therefore the bore of 19 millimeters diameter is certainly the best for general purposes."]

[The silver flute with a wood head which is shown in Fig. 10 has a bore of 20 millimeters; it is the only flute in C of this bore which the translator has ever seen. Its tone quality was directly compared with that of the flute shown in Fig. 9, having a bore of 19 millimeters. The result of the comparison was to corroborate the opinions of Boehm as expressed above.]

[Boehm later made the "Alt-Flöte," commonly called the "Bass Flute," which is described in section XII; the tube of this instrument has an inside diameter of 26 millimeters. Messrs. Rudall, Carte and Company make an "Alto Flute" in B♭, having a bore of 20.5 millimeters. These instruments have the beautiful tone quality in the lower octaves, referred to above.]

A second obstacle which compelled me to depart from the theory was the impossibility of making a moveable cork or stopper in the upper end of the flute, so that its distance from the center of the embouchure might be increased or decreased in proportion to the pitch of each tone; a medium position for it must therefore be used which will best serve for the highest as well as the lowest tones; this is found to be 17 millimeters from the center of the embouchure.

Next, the size and form of the mouth-hole (embouchure) must be determined. The tone producing current of air must be blown against the sharp edge of the mouth-hole, at an angle which varies with the pitch of the tone. When the air stream strikes the edge of the hole it is broken, or rather divided, so that one part of it goes over or beyond the hole, while the greater part, especially with a good embouchure, produces tone and acts upon the column of air enclosed by the tube, setting it into vibration.

By this means the molecular vibrations of the tube are excited, producing a tone as long as the air stream is maintained; it follows therefore that the tone will be stronger the greater the number of the air particles acting upon the tone producing air column in a given time. The opening between the lips through which the air stream passes is in the form of a slit, and a mouth-hole in shape like an elongated rectangle with rounded corners, presenting a long edge to the wide air stream, will allow more air to be effective than would a round or oval hole of equal size.

For the same reason a larger mouth-hole will produce a louder tone than a smaller one, but this requires a greater strength in the muscles of the lip, because there is formed a hollow space under the lip which is unsupported. More than this it is difficult to keep the air current directed at the proper angle, upon which the intonation and the tone quality for the most part depend.

By a greater depression of the air stream towards the middle of the hole, the tone becomes deeper and more pungent, while a greater elevation makes the tone higher and more hollow. Consequently the angle between the sides of the mouth-hole and the longitudinal section through the axis of the air column, as well as the height of these sides, has an important influence upon the easy production of the tone. In my opinion an angle of 7 degrees is best adapted to the entire compass of tones, the walls being 4.2 millimeters thick; and a mouth-hole 12 millimeters long and 10 millimeters wide, is best suited to most flute players.

After the completion of these experiments I constructed many thin, hard-drawn tubes of brass upon which the fundamental tone C_8

and also higher notes could be produced by a breath, and easily brought to any desired strength without their rising in pitch.

The hissing noise heard in other flutes not being perceptible served to convince me that the correct dimensions of the tube and its smooth inner surface permitted the formation of the air waves without noticeable friction. From this as well as from the fine quality of tone of the harmonics or acoustical overtones, can be inferred the perfect fitness of my tube for the flute; and with this I began the determination of the shortening or cutting of the air column, required for producing the intervals of the first octave.

The simplest and shortest method is, naturally, to cut off from the lower end of the flute tube so much as will make the length of the air column correspond to each tone of the chromatic scale. To accurately verify these proportions, I made a tube in which all the twelve tone sections could be taken off and again put together, and which was provided with a sliding joint in the upper part of the tube to correct for any defects in tuning.

Since a flute cannot be made to consist of many separate pieces, all the tone lengths must be combined in one tube, and these lengths may be determined by laterally bored holes; the air column may be considered as divided or cut off by these holes in a degree determined by the ratio between the diameters of the holes and of the tube.

The air column, however, is not as much shortened by a tone-hole as by cutting the tube at the same point. Even if the size of the hole is equal to the diameter of the tube, yet the air waves will not pass out of the hole at a right angle as easily as along the axis.

The waves meet with a resistance from the air column contained in the lower part of the tube, which is so considerable that all the tones are much too flat when they come from holes placed at the points determined by cutting the tube. And, moreover, the height of the sides of the holes adds to the flattening effect. The tone-holes must, therefore, be placed nearer the mouth-hole the smaller their diameter and the higher their edges.

Although one octave can be correctly tuned in this manner with small holes, yet for the following reasons it is greatly to be desired that the tone-holes should be as large as possible.

1. Free and therefore powerful tones can only be obtained from large holes which are placed as nearly as possible in their acoustically correct positions.

2. If the holes are small, and are considerably removed from their proper places, the formation of the nodes is disturbed and rendered uncertain; the tone is produced with difficulty, and often breaks into other tones corresponding to the other aliquot parts of the tube [harmonics].

3. The smaller the holes, the more distorted become the tone waves, rendering the tone dull and of poor quality.

4. The pure intonation of the third octave depends particularly upon the correct position of the holes.

From accurate investigations it is shown that the disadvantages just mentioned, become imperceptible only when the size of the holes is, at the least, three fourths of the diameter of the tube [14¼ millimeters]. But in the manufacture of wooden flutes, the making of holes of such a size causes considerable difficulty. At first it appeared very desirable to make the holes of gradually increasing size from the upper to the lower ones; later this proved to be exceedingly disadvantageous, and I concluded that again a medium course is the best. Therefore I finally chose a constant diameter for all the twelve tone-holes from C_3 to C_4, which for silver flutes is 13.5 millimeters, and for wooden flutes 13 millimeters.

[Several *Boehm & Mendler* flutes, of wood and of silver, which have been measured by the translator, show exactly the diameter of holes mentioned above. The reason why graduated holes are disadvantageous is no doubt given in the following extract of a letter written by Boehm, in 1862, to Louis Lot, the celebrated flute maker of Paris: "The flute-playing world knows that for six years I made all my silver flutes with graduated holes. * * * The graduated holes are, in my opinion, the best, but the difference is scarcely appreciable. I have discontinued making them on account of the greater difficulty in the manufacture." The last sentence seems to state the three facts bearing on the question: the graduated holes are the best; their superiority is slight; the cost of their manufacture is greater. Today nearly all makers use two sizes of holes, and one eminent maker uses four.

With these dimensions, in order to produce the correct pitch, the center of the $C_3\sharp$ hole must be moved 5 millimeters above the point at which the tube would have to be cut off in order to produce the same tone. The amount of removal increases with each hole in the ascending scale, so that the C_4 hole [thumb key hole] must be placed 12 millimeters above the point of section of the air column. In this manner the correct positions of the holes are obtained, and the tuning of all the notes of the first octave is rendered to the ear as perfect as possible.

The notes of the second octave are produced, as it were, by overblowing the tones of the first, by narrowing the opening in the lips, and by changing the angle and increasing the speed of the stream of air; this results in producing shorter tone-waves.

In order to secure a greater compass of tones, it is necessary to use a narrower tube than the one best suited to the fundamental tone; or in other words a tube too narrow in proportion to its length. From this it results that the tones D_4 and $D_4\sharp$ are of different quality from the next following, and it is first with the note E_4 that the relation between length and width is again restored.

For joining C_4 and E_4, therefore, the flute should properly have three additional large holes for the tones $C_4\sharp$, D_4 and $D_4\sharp$. But there is only one finger available, and this must be used for the $C_4\sharp$ hole which must be so placed that it may serve at the same time as a so-called vent hole for the tones D_4, $D_4\sharp$, D_5 $G_5\sharp$ and A_5. Theory, however, requires octave-holes for D_4 and $D_4\sharp$, which would also serve as vent holes for the twelfths, $G_5\sharp$ and A_5, giving to all these tones a better quality, a purer intonation and a freer sounding.

But since I was unwilling to make my system of fingering more complicated, it was necessary to determine by experiment a size and position for the $C_4\sharp$ hole which would satisfy all of these demands. The $C_4\sharp$ hole, as well as the two small holes for the D_4 and $D_4\sharp$ trill keys, must therefore be placed considerably above their true positions, and must be made correspondingly smaller.

For the exact determination of these, as well as for the other tuning proportions, I had a flute made with moveable holes, and was thus enabled to adjust all the tones higher or lower at pleasure. In this way I could easily determine the best positions of the upper three small holes, but it was not possible to determine the tuning of the other tones as perfectly as I desired; for, endeavoring to produce an entire pure scale in one key, the tones were always thrown out of the proportions of the equal temperament, without which the best possible tuning of wind instruments with tone-holes cannot be obtained.

Therefore, in order to determine with perfect accuracy the points at which the tone-holes shall be bored, one must avail himself of the help of theory. To form a basis for all the calculations of dimensions, and for the easy understanding of this, it seems not out of place to give as simply as possible an explanation of the fundamental acoustical laws.

As is known, the acuteness or graveness of tones depends upon the length and volume of the sounding body, and is proportional to the velocity of vibration which can be impressed upon the body. For the entire extent of musical tones, these constant relative proportions have long been known with mathematical precision; the following Table I gives these relations for all the tones of the equally tempered scale in the form of vibration numbers and string lengths. [The ratio of the number of vibrations of any tone in the equally tempered scale to the number of vibrations of the preceding tone is the twelfth root of 2; the numerical value of this ratio is 1.059463. As the numbers in this table are useful for various acoustical computations, they have been recomputed by the translator, and several typographical errors in Boehm's figures have been corrected.]

TABLE I

TONES	RELATIVE VIBRATION NUMBERS	RELATIVE STRING LENGTHS
C_{x+1}	2.000000	0.500000
B	1.887749	0.529732
B♭ or A♯	1.781797	0.561231
A	1.681793	0.594604
A♭ or G♯	1.587401	0.629960
G	1.498307	0.667420
G♭ or F♯	1.414214	0.707107
F	1.334840	0.749154
E	1.259921	0.793701
E♭ or D♯	1.189207	0.840896
D	1.122462	0.890899
D♭ or C♯	1.059463	0.943874
C_x	1.000000	1.000000

Here is shown the geometrical progression in which the vibration frequency of C_x, which is designated the fundamental, is constantly increased throughout the scale, so that the number of vibrations of the octave, C_{x+1}, has become double that of C_x; at the same time, shortening in equal progression, the string-length is reduced from 1.0 to 0.5.

With these relative numbers it is a simple matter to calculate the absolute vibration numbers corresponding to any desired pitch, since any given vibration number bears to all the other intervals exactly the same proportion, as the relative number corresponding to this tone bears to the relative number of these other intervals.

For example, to calculate the number of vibrations of the tone C_3, knowing the absolute number of vibrations of the Normal A_3 to be 435 vibrations per second, we have the following proportion:

$$\text{relative } A_3 : \text{relative } C_3 = \text{absolute } A_3 : \text{absolute } C_3$$

$$1.681793 : 1.000000 = 435 : x$$

$$\frac{435 \times 1.000000}{1.681793} = 258.65.$$

If now this absolute number 258.65 be multiplied by each of the relative vibration numbers of the above table, one obtains the absolute vibration numbers of all the tones in one octave of the normal scale from C_3 to C_4. In this way one avoids the division by numbers of many places, which is necessary by the direct method of calculation.

In a similar way one calculates measurements of length, as soon as the theoretical length of the air column in any given system, corresponding to the string length 1.000000, is determined.

While the vibration numbers and theoretical proportions of lengths for all instruments remain always the same, yet the actual lengths of the air columns are very different, because each wind instrument has its own peculiar length in consequence of its tone formation. For example, an oboe and likewise a clarinet (on account of the flattening effect upon the tone of the tube and mouth-piece) are much shorter than a flute of the same pitch; and even in the flute the actual length of the air column is less than the theoretical length corresponding to the given tone. The same is true to a less extent of a simple tube or a mouth-piece alone. Hence it happens that a wind instrument cut in two in its middle does not give the octave of its fundamental, but a considerably flatter tone.

In the case of the flute the flattening influence of the cork, the mouth-hole, the tone-holes, and the dimensions of bore is such that, altogether, it amounts to an air column of 51.5 millimeters in length, which in the calculation must be considered theoretically as existing, in order that the length of the air column shall exactly correspond to the length of the string of the monochord determined from the numbers and proportions of the table.

It will be found that the actual length of air column (and therefore also of the flute tube) from the center of a C_3 hole, bored in the side of a long flute tube, to the face of the cork 618.5 millimeters, and that the length of the first octave from C_3 to C_4 is 335 millimeters, thus the upper portion is 51.5 millimeters shorter than the lower, and in calculating, this quantity (51.5 millimeters), must be taken into consideration.

By doubling the length of the octave one obtains as the theoretical air column the length of 670 millimeters, which serves as the unit of calculation, and from which, corresponding to the normal pitch, are obtained the following absolute vibration numbers and relative and actual length measures. [The numbers in this table have been recomputed by the translator.]

TABLE II

TONES	ABSOLUTE VIBRATION NUMBERS	THEORETICAL AIR COLUMN LENGTHS	ACTUAL AIR COLUMN LENGTHS
C_4	517.31	335.00 mm	283.50 mm
B_3	488.27	354.92	303.42
$B_3\flat$ $A_3\sharp$	460.87	376.02	324.52
A_3	435.00	398.38	346.88
$A_3\flat$ $G_3\sharp$	410.59	422.07	370.57
G_3	387.54	447.17	395.67
$G_3\flat$ $F_3\sharp$	365.79	473.76	422.26
F_3	345.26	501.93	450.43
E_3	325.88	531.78	480.28
$E_3\flat$ $D_3\sharp$	307.59	563.40	511.90
D_3	290.33	596.90	545.40
$D_3\flat$ $C_3\sharp$	274.03	632.40	580.90
C_3	258.65	670.00	618.50

Evidently for the practical application, 51.5 millimeters must be subtracted from each of the theoretical lengths to obtain the actual lengths given in the third column, which determine the distances between the face of the cork and the center points for boring the tone holes.

III. EXPLANATION OF THE SCHEMA

In Table II there is given only one set of normal dimensions; since the normal pitch [now known as international or low pitch: A=435] is by no means in universal use, it is often necessary to have measurements corresponding to various given pitches, but the labor required to make the requisite dimension calculations costs much time and trouble.

These inconveniences have caused me to design a "Schema" in which the basis of all the calculations of measurements of length is graphically represented. In this diagram the geometrical proportions of the lengths of a string, corresponding to the reciprocals of the vibration numbers in the equally tempered scale, are represented by horizontal and vertical lines; while diagonal lines indicate the geometrical progression in which the length measures may be varied without disturbing their reciprocal proportions to the vibration numbers.

This graphic method was suggested by the plan of a monochord, on which by means of a moveable bridge the stretched string may be gradually shortened to half of its entire length, thereby producing all the intervals of one octave.

Now these proportions remain constant from the highest to the lowest musical tones, and the transition

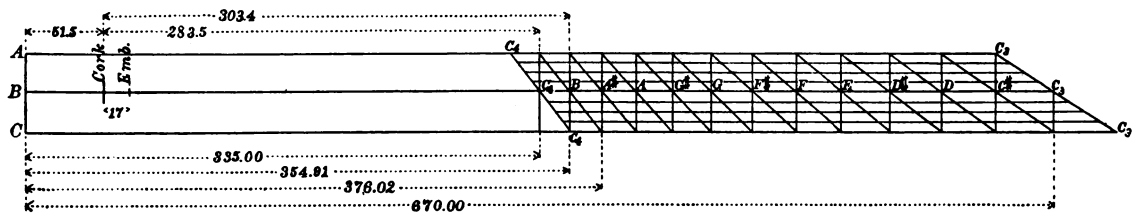

FIG. 3.

Schema for Determining the Positions of the Tone-Holes
upon Wind Instruments at Various Pitches

from one interval to the next can therefore be represented graphically, and my *Schema* has been founded upon these considerations. With its help and without calculation, the centers of the tone holes of all wind instruments constructed on my system, as well as the positions of the so-called frets of guitars, mandolins, zithers, etc., may be easily and quickly determined.

My diagram, Fig. 3, consists of three parallel horizontal lines of three different lengths, which start from a common vertical line, and are designated by *A, B,* and *C*. [In the original this diagram is given in half-size scale; it is here reproduced about one-fifth full size. In either case, for actual use, it would need to be accurately redrawn to full size. The dimensions shown on the diagram have been added by the translator, to make its construction plain; all the dimensions are contained in Table II. A portion of the *Schema* drawn to full size, with dimension added, is shown in Fig. 4, on page 27.]

The central line represents the air column of a cylindrical flute tube, open at both ends, corresponding to the stretched string of the monochord, whose fundamental tone is C_3 of the scale founded on the normal pitch $A_3 = 435$ vibrations. The entire length of this air column, and therefore of the line *B*, for the fundamental tone C_3 is 670 millimeters. The sectional lengths for the tones of the chromatic scale, calculated from the absolute vibration numbers for this pitch, and expressed in millimeters [see Table II], are given by the points of intersection of the line *B* with the vertical lines.

There is thus represented a standard of measurement, expressed in millimeters, to be taken from the upper end of the diagram along the line *B*. This diagram gives the actual dimensions of my flute, measured from the cork, if from each relative measure is subtracted the 51.5 millimeters (represented by the small cross line) which was previously added to complete the theoretical air column [see page 18]. More than this, all the data for calculation are present, if beneath the points of intersection of the length measures the absolute vibration numbers are written.

Since these standard measures correspond only to the normal pitch, it is necessary to be able to lengthen or shorten the reciprocal distances of the tone-holes to correspond to varying pitches, with ease and without disturbing their reciprocal proportions.

This can be accomplished without computation by means of diagonal lines on the diagram which pass through the points of intersection of the vertical lines with the line *B*, both upwards and downwards to the points where the vertical lines end in the two parallel lines *A* and *C*. In this way are shown two new sets of measures, one corresponding to a pitch a half tone sharper, the other to one a half tone flatter.

A flute made to the shortened measurements of line *A*, will be exactly half a tone sharper than the normal pitch, while one made upon the longer dimensions of line *C*, will be exactly a half tone lower than the normal pitch. Now as these diagonal lines may be looked upon as continuous series of tone-hole centers, which, in a geometrical progression, gradually approach each other above, and in the same way recede from each other below, it follows that the relative proportions of the distances of these points remain continually unchanged, wherever the diagonal lines are intersected by a new line parallel to the line *B*.

It is possible therefore, as shown in the diagram, to draw between the lines *A, B,* and *C* six parallel lines, whose pitch difference is one eighth of a tone; and at will many other lines may be drawn, the intersections of each of which with the diagonal lines will give correct dimensions. The only remaining question is which of these new lines will correspond to a given pitch.

In order to answer this question one must first express the pitch difference between the given pitch and the normal, in millimeters, which will give the difference between the length of the air column of the given tone, and the length for the same tone in normal pitch shown on line *B*. This will also determine the position of a new vertical section line crossing the line *B,* corresponding to the given tone.

If the desired pitch is higher than the normal, the vertical section line through the point on line *B,* corresponding to the new pitch, is to be extended upward toward *A;* while if the pitch is lower than the normal, the vertical line is to be extended downward toward *C*.

In either case the intersection of the vertical line with a diagonal line is the point through which a new line parallel to *B* is to be drawn. The conversion of pitch difference into longitudinal measurement may be carried out as follows. The pitch to which an instrument is to be constructed may be given by a tuning fork, a tuning pipe, or by number of vibrations, and in the rules either an A or a C may be used.

For example let there be given by a tuning fork an A_3 of 430 vibrations which is 5 vibrations flatter than the normal A_3 of 435 vibrations. In this case it is necessary merely to draw out the head joint of a normal flute until it is exactly in tune with the tuning fork (which naturally the ear determines), in which case the length drawn out will be found to be 4.63 millimeters. If, however, the given pitch is higher than the normal, for example $A_3 = 445$ vibrations, then, since the flute cannot be shortened, the head joint is to be drawn out till the tone B♭ is in unison with the A_3 of the fork. The length drawn out will be found to be 13.40 millimeters; and since the distance between the centers of the B_3♭ and A_3 holes of the normal flute is 22.36 millimeters, it follows that the air column corresponding to the A_3 of the fork is shorter than that of the normal flute by 8.96 millimeters.

If the pitch differences are given by vibration numbers, then the conversion into millimeter measures must be calculated. The vibration numbers are inversely proportional to the lengths; and the vibration numbers $A_3 = 430$ and $A_3 = 445$ are to the normal vibration number $A_3 = 435$, as the relative normal length 398.38 millimeters is to the required lengths. If now the numbers 435 and 398.38 are multiplied together, and the resulting product is divided by the numbers 430 and 445, the quotients are 403.01 and 389.42 which then represent the numbers of millimeters in the relative lengths, to which the vibration numbers have been converted. If these measurements correspond to the given vibration numbers 430 and 445, then the differences between them and the length of the normal A_3, 4.63 and 8.96 millimeters, must correspond to the vibration differences of 5 and 10 vibrations.

Therefore a vertical section line drawn through the line *B* at a point 4.63 millimeters distant from the center of the A_3 hole in the direction of $A_3\flat$, will correspond to $A_3 = 430$ vibrations; and a section line 8.96 millimeters distant from the A_3 hole in the direction of $A_3\sharp$ will correspond to $A_3 = 445$ vibrations.

[Boehm's original description of the *Schema* was published in the *Kunst und Gewerbeblatt* in Munich, October, 1868. In this account a diagram accompanies the preceding explanation, but it is omitted in *"Die Flöte."* In Fig. 4 this drawing is given, with some elaboration. It shows, drawn accurately to full scale, a portion of the *Schema*. The ratio of the distances between the parallel lines *A, B,* and *C* is obviously the same as of the distances between any three successive vertical lines.]

The desired points of intersection will, in the manner mentioned above, be obtained from the diagonals leading upward or downward, and the results of this method of procedure will be found to be perfectly accurate.

Since the relative proportions of the numbers of vibration and the measurements remain unchanged throughout the diagram, it is immaterial whether the given tone is an A, a C, or any other; and if the diagram is not sufficiently long for lower tones, it can be extended at will.

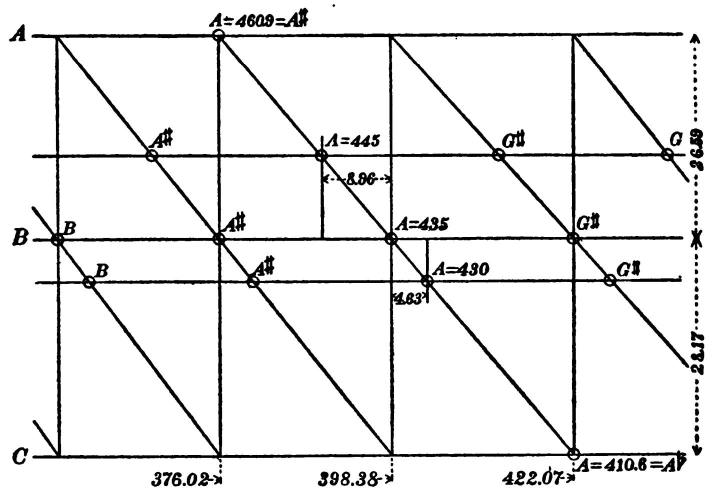

FIG. 4. A Portion of the Schema
Actual Size

For each successive lower octave one has only to double all the dimensions; the accuracy of the drawing controls itself, for any error made would be at once evident by the drawing of the diagonal lines.

From this explanation it is evident that a flute can be in the most perfect tune at one pitch only, and that any shortening or lengthening above the tone-holes must work disadvantageously upon the intonation; in the first case the higher tones as compared with the lower are too sharp, and in the second case [drawing the tuning side], on the contrary, the lower tones are too sharp as compared with the higher.

Obviously, these difficulties are no more overcome by a longer or shorter head joint, than by a simple drawing of the slide; this drawing out must not be more than two millimeters. Small pitch differences can, indeed, be compensated, so far as the ear is concerned, by a good embouchure. Accordingly I make the head joints of my flutes about two millimeters shorter than is required for perfect tuning, so that one may not only draw out the head to lower the pitch, but that he may make it somewhat sharper. However it is best in ordering a flute to specify the pitch as accurately as possible, and at the same time to mention whether the player directs his embouchure inwards or outwards, as this also produces a considerable effect on the pitch.

IV. THE MATERIAL

THAT the tones of a flute may not only be easily produced, but shall also possess a brilliant and sonorous quality, it is necessary that the molecules of the flute tube shall be set into vibration at the same time as the air column, and that these shall, as it were, mutually assist one another. The material must possess this requisite vibration ability, which is either a natural property of the body, for example as in bell-metal, glass and various kinds of wood, or has been artificially produced, as in the case of hardened steel springs and hard-drawn metal wire.

Now in both cases the excitation of the vibrations requires the expenditure of energy proportional to the mass of the material. Consequently the tones of a flute will be more easily produced and the development of their full strength will require less effort in blowing, the less the weight of the flute tube.

Upon a silver flute, therefore, the thin and hard drawn tube of which weighs only 129 grams, the brightest and fullest tone can be brought out and maintained much longer without fatiguing blowing, than can be done on a wood flute, which even when made as thin as possible still has double the weight, namely 227½ grams. [Boehm's silver flute, complete, weighs about 330 grams, being considerably lighter than those of most other makers.]

Any variation in the hardness or brittleness of the material has a very great effect upon the timbre or quality of tone. Upon this point much experience is at hand, for flutes have been made of various kinds of wood, of ivory, crystal-glass, porcelain, rubber, papier-mâché, and even of wax, and in every conceivable way to secure the various desired results. Heretofore all of these researches have led back to the selection of very hard wood, until I succeeded in making flutes of silver and German silver, which now for twenty years have rivaled the wood flute. [Silver flutes were first introduced by Boehm in 1847.] Notwithstanding this it is not possible to give a decisive answer to the question "What is the best?"

The silver flute is preferable for playing in very large rooms because of its great ability for tone modulation, and for the unsurpassed brilliancy and sonorousness of its tone. But on account of its unusually easy tone-production, very often it is overblown, causing the tone to become hard and shrill; hence its advantages become of full value only through a very good embouchure and diligent tone practice. For this reason wooden flutes on my system are also made, which are better adapted to the embouchures of most flute players; and the wood flutes possess a full and pleasant quality of tone, which is valued especially in Germany.

The silver flutes are made of a $\frac{9}{10}$ fine alloy [United States coin silver is $\frac{9}{10}$ fine; sterling silver is $\frac{925}{1000}$ fine]; and for the manufacture of wood flutes I usually employ either the so-called cocus wood, or the grenadille wood of South America. The first, of dark or red-brown color, is especially desirable because of its brilliant tone, notwithstanding that this wood contains a resin, which, in very rare cases, induces an inflammation of the skin of the lip. To obviate this difficulty, as well as to secure a very pleasant ringing quality of tone in the high notes, many will prefer black grenadille wood. Ebony and boxwood are now used only for the cheaper grades of instruments.

For my flutes only selected good and perfect wood is employed, and if a piece develops a defect during the working, it is at once cast aside, that no more time and labor may be lost.

However, a flute which is entirely free from faults may become cracked by improper handling, against which no guarantee is possible. Both the cause and the means of preventing such accidents should be understood, and I will therefore return to this subject later, under the heading, Treatment of the Flute in General.

[Boehm frequently combined two materials, making the body of silver and the head of wood. It was in his later years that he most strongly advocated this combination, though he had constructed such flutes in his earlier years, certainly prior to 1866. A silver flute with a wood head, the latter "thinned" and without metal lining, is shown in Fig. 10. Notwithstanding Boehm's recommendation, such composite instruments have not grown in favor.]