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## Acoustical Investigation of the Japanese Bamboo Pipe, Syakuhati.

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*With 3 plates.*

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Of all our wind instruments the *syakuhati* has for more than two centuries been one of the most popular with our people. Its origin is probably to be traced back to a similar pipe called the *hitoyogiri*, which was already popular under the Asikaga Shōgunate. It had been originally an inseparable accompaniment of a sect of itinerant Buddhist priests called *komusō*, and special melodies were composed for it. The characteristic color of its notes gave it a peculiar hold upon the fancy of the nation, which has steadily grown stronger until to-day it has become so popular that every favourite air is played on it and even a special system of written music has been developed for the instrument.

The timbre of the notes of the *syakuhati* somewhat resembles that of a flute and also that of an oboe, being peculiarly pathetic and of a rural color. The characteristic variety of expressions and tone-colors, of which it is capable is not attainable by any other instrument of the kind.

The name *syakuhati* is derived from the length of the pipe, which is 1 *syaku*<sup>1</sup> and 8 (*hati*) *sun*, for the Japanese key *itikotu* (d). However, in pipes in popular use the length differs, varying from ca. 1.2 *syaku* to 2.1 *syaku*. To give the octaves of the proper *syakuhati* a pipe 1.2 *syaku* long is used. Of late, the instrument has been occasionally played with a violin, in unison after the Japanese manner. In this case the length of the pipe is 2.1 *syaku*, giving c, for the gravest tone.

Moreover, a simple melody is often played in unison with two pipes of different lengths, 1.7 and 1.9 *syaku*, using different positions of the finger-holes for the two pipes, whose gravest tones differ by an interval of a whole tone.

The pipe is cut from well seasoned bamboo (*Phyllostachys Quilioi*, Riv.) near its root in such a way that both its ends correspond to knots in the bamboo. The compactness of the tissues is the important factor determining the quality of the note. The bamboo must be neither too hard nor too soft. This compactness is in some measure estimated from its density. There is a traditional receipt for the choice of the bamboo viz., that a proper *syakuhati* with a periphery of 3.7 *sun* at the uppermost finger hole, must have weight of about 100 *momme*=375 gr., when perfectly dried.

In Pl. I, is reproduced a photograph of a *syakuhati* in the possession of Mr. R. Uehara of the Tōkyō Musical Academy, a virtuoso on the instrument. The pipe has five lateral openings, four in front, the uppermost being at the back. The centre of the upper front hole is always a little above the middle of the pipe. The lengths occupied by the consecutive front holes are ca. 1/9.5 of the total length. The distance between the back hole

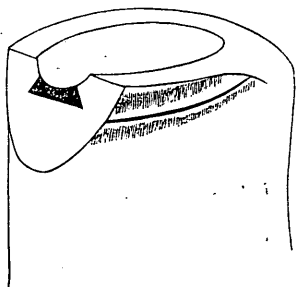
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1 1 *syaku*=10 *sun*=0.30303 m.

and the upper front hole measured along the length of the pipe is ca. 0.75 of the length occupied by the consecutive front holes.

The number of knots of a proper *syakuhati* must be seven. Of these the two at the ends, and the one immediately below the lowest hole, i.e. about 3 *sun* from the lower end, are considered very important for giving strength to the pipe and for insuring the proper tuning. The latter, on this account, has received the special name, *gorobusi*. Between this knot and the lower end, two or three knots are required. According to the natural distribution of knots in the bamboo plant, the distances between consecutive knots increase toward the upper end of the pipe. In the traditional form of the *syakuhati*, the distances between consecutive knots, excluding those situated between the *gorobusi* and the lower end, must form a harmonic series of 3, 4, 5 and 6 *sun*, making 18 in all. Such an ideal form is rarely met with. Also the fact that the two ends must correspond to knots, greatly restricts the choice of the bamboo. To obviate this difficulty, an improvement has recently been made which consists in joining up the pipe from two separable halves. This modification alters the quality of the pipe in no sensible way.

The lower part of the pipe usually bends forward with a slight curvature. The most conspicuous feature of the instrument is the embouchure. It is called the *utaguti* (*uta*=song; *kuti*=mouth)

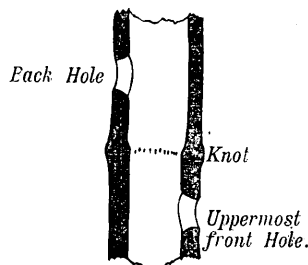


as in other wind instruments of the kind. A part of the thick wall in front of the upper end is beveled with a plane making an angle of about  $30^\circ$  with the downward direction of the length, so that a portion of the inner wall forms a sharp

knife-edge. For the bamboo knife-edge an imbedded piece of horn, whale bone, ivory, etc., is usually substituted to prevent wearing. The back part of the upper end is rounded off with a slight inclination backward, so that when the end is applied between the lower lip and the chin, it may fit uniformly to the chin. The general aspect of the embouchure may be seen in the annexed figures.

The interior of the pipe is cleared of the septa at the knots and carefully varnished with reddish Japanese lacquer. In some pipes, the septa are entirely removed, so that in the interior no abrupt change of the section exists; whereas, in other pipes, the septa are imperfectly removed so that in the joint below each knot, the section of the pipe is slightly narrowed. In any pipe, the inner diameter decreases slightly toward the *gorobusi* at which the section is narrowed somewhat abruptly. Below this contraction, the calibre is uniform, or gradually widens towards the lower end, according to the fancy of the constructor.

The lateral openings are generally of a circular or slightly elliptical shape. Their areas are determined with some proportion to the sectional area at the *gorobusi*. For many pipes the third hole, counted from the lower end, is made a little narrower than the others, in order to secure the proper tuning. The hole gradually widens toward the inside, as shown in the annexed figure, which shows a portion of the longitudinal section of a pipe. Generally, the position and width of each hole slightly differ for different pipes, according to the irregularities of the sections. Irregularities on the inside of the lateral openings more or less affect the pitch of overtones.



The lacquering of the inner wall is necessary in order to secure the easy production of the notes. A roughness of the interior also prevents the clearness of the notes, and lowers the pitch sensibly. If the inside of an unvarnished pipe be wet throughout with water, its note is remarkably improved.

In playing the pipe, the embouchure is applied between the lower lip and the chin so that a narrow arcular aperture is left between the lip and the knife-edge, upon which the jet of air from the mouth is directed. The pipe is held by its lower part between the thumb and the middle finger of the right hand so that the middle finger rests midway between the lower pair of front holes. The left hand holds the upper part of the pipe, the thumb corresponding to the back hole, and the middle finger being placed between the upper pair of front holes. The distribution of the other fingers will be understood. The lower end of the pipe should be placed a few cm. above the right knee when the player is seated. To produce the note, the lips must be contracted a little, so as to rightly direct the jet of air upon the knife-edge. Thus, the cavity of the mouth of the player, the narrow opening between the lips and the knife-edge, taken as a whole, makes up a special form of the embouchure of an organ pipe. The adjustment of the lips is not an easy matter for beginners so that for most persons it takes a week of training, before a tolerable clear sound is produced.

The most conspicuous characteristic of this pipe is that the pitch of the several notes corresponding to the different positions of the holes, may be varied within a wide range, by simply adjusting the area of the arcular aperture of the embouchure. This adjustment is usually made by changing the inclination of the head of the player, relative to the pipe. The angle through

which the adjustment may be made measures about  $10^0$ , producing a change in the note of more than a semitone. To raise or lower the note, the head is inclined so that the arcular aperture is slightly widened or narrowed, while the pipe is held almost immovable. The raising or lowering of the pitch produced in this way is called respectively the *kari* or *meri* of the sound. Besides this adjustment, a slight lowering of the pitch is often effected by placing the finger immediately above the corresponding hole, so as to prevent free communication of air through the hole. This adjustment, the action of which is called *kazasu* is rather difficult, so that it is only made by virtuosi. Since, in this way, the compass of the notes for consecutive positions overlap each other, the instrument is capable of producing almost *any note* within a range of nearly two octaves, notwithstanding the small number of its lateral openings.

In short, the instrument is to be regarded as an ingenious form of organ pipe which produces a continuous gradation of notes. In this respect, the *syakuhati* may be compared to a string instrument such as a violin rather than to wind instruments of its kind. The smooth slurring of the note by a semitone which is frequently met with in many Japanese melodies, executed on this instrument, is peculiarly sweet. The extraordinary variability of the note makes the technics of the pipe much more difficult than in the case of other instruments. Except when guided by a good ear, the homophonic performance of a melody by two *syakuhati* is not an easy matter.

It may be added that beginners are apt to make the mouth opening too narrow by a striving to produce the notes, so that the pitch are generally lowered.

The principal objects of the present investigation are to

examine the special function of the mouth in producing the varieties of the notes and also to study the effects of the lateral openings in general. The latter part, therefore, may be applied to any other instrument with lateral openings. In addition, the effect of obstacles placed inside the pipe is dealt with, with reference to the knots of the *syakuhati*.

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## RESULTS OF THE EXPERIMENTS.

### 1. Notes in different Positions.

The *syakuhati* upon which the experiments were made, was of the following dimensions:

The length of the pipe from end to end = 49.2 cm.

The distances of the centers of the holes from the upper end = 19.8, 23.4, 28.3, 33.3 and 38.2. cm.

The mean diameter of the finger-holes = 0.9 cm.

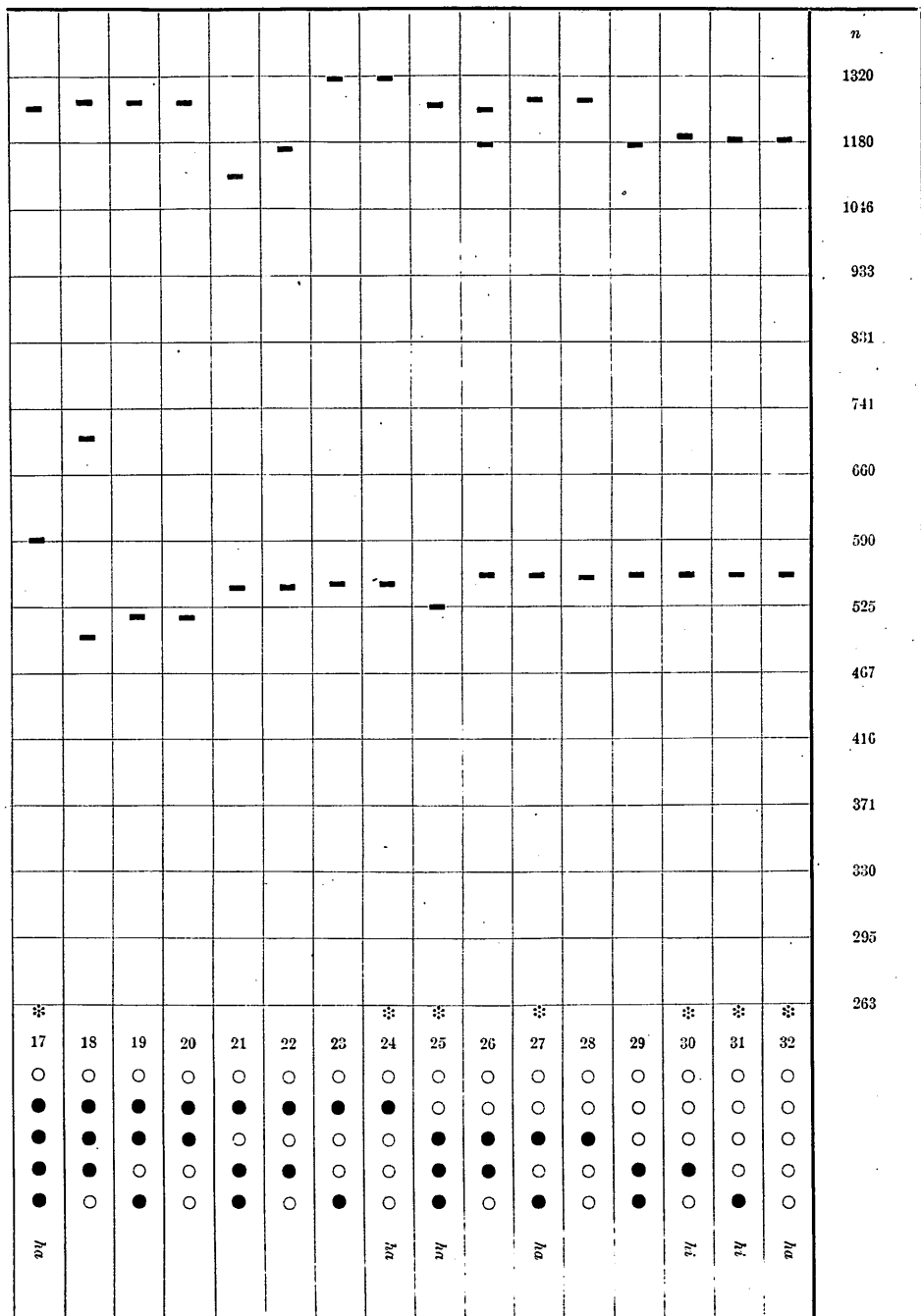
The diameter of the section immediately inside the mouth = 1.9 cm.

Ditto at the *gorobusi* = 1.5 cm.

Approximate pitches of the notes for all the possible combinations of holes for a nearly constant width of the mouth are tabulated as follows:—







The pitch for each position varies of course with different widths of the opening of the embouchure, with the pressure of the breath, and also with the degree of the opening of the finger-holes. In the above table, the fundamental tone was obtained by a very light breath-pressure in order that it might not deviate much from the natural pitch; on the contrary, the overtone can be obtained only by somewhat strong pressure. When blown forcibly as in actual playing, the fundamental tone is raised about a semitone so that the overtones for the positions 1, 2, 4, 8, 16, 17, 30, 31, 32 become the octaves of the corresponding fundamental tones. It will be noticed that the overtones of the other positions are very much complicated with respect to their fundamental notes. While the fundamental notes are generally lowered more or less by closing the hole below the uppermost open one, the contrary is often the case with the overtones as in the positions 5, 7, 9, 10, 12, etc. Besides, an overtone much lower than the octave is met with in the position 9 and 18.

## 2. Correction for the Mouth.

How much the natural pitch of the pipe is influenced by varying the area of the mouth-opening may be shown by the following simple experiment. The embouchure is brought to the lip, as in playing. Bring a proper vibrating tuning fork near the embouchure and adjust the aperture so that the resonance is maximum. If the pipe be slightly inclined from this position or if the lower lip be slightly moved, the resonance at once falls.

For an ordinary organ pipe of a circular section, the correction which is to be added to its length in order to obtain the fractions of the wave length, is according to Cavallé-Coll,  $3\frac{1}{2} R$ ,

where  $R$  is the sectional radius of the pipe. Lord Rayleigh<sup>1)</sup> pointed out that the greater part of it is due to the embouchure. As far as I am aware, there has been no further experimental investigation with respect to the details of the relations between the dimension of the embouchure and the correction due to it.

In the case of the *syakuhati*, the mouth opening is very narrow, being an arcular passage between the lip and the sharpened edge of the embouchure, so that the correction of the length due to the embouchure may be expected to be very great. As may be seen later, it is in some cases ten times the sectional area of the pipe.

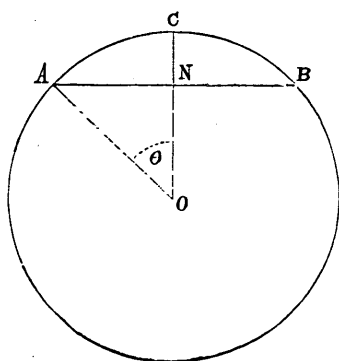
To study the effect of the embouchure directly on the *syakuhati*, is not very easy, 1) because the determination of the area of the irregular mouth-opening between the lip and the edge, is difficult; the more so, since the area is varied seriously by a slight motion of the lip; 2) because the effect of the lateral openings interferes with that of the embouchure if we wish to examine the cases for various notes. I sought, therefore, for a simple form of resonator which was similar to the *syakuhati* in the essential form of the embouchure and which enabled me to study the effect of the embouchure only, free from the complications due to the lateral openings. The experiment made for this purpose was as follows.

A glass pipe with a fairly uniform inner diameter of 3.95 cm. and a thickness of 2.7 mm., was fixed vertically. The upper, open end was polished carefully, while the lower end was stopped with a cork, through a hole in which a small glass tube was inserted. Through this small tube, water was introduced

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1) Rayleigh. Phil. Mag. (5), 3, 462. 1877.

into or removed from the lower part of the pipe, in order to adjust the length of the air column inside the pipe at will. A thin plate of zinc, 0.4 mm. thick, was fastened on the open



end to cover it partially, leaving a segmentary aperture between its straight edge and the edge of the pipe. In order to secure a close contact between the plate and the polished end of the pipe, a small quantity of tallow was applied to the place of contact. The area of the segmentary aperture was calcu-

lated from the length of the arrow. In the annexed figure, the area of the segment ABC is given by

$$r^2\theta - \frac{r^2}{2}\sin 2\theta,$$

where

$$\theta = \cos^{-1} \frac{r-p}{r},$$

$r$  being the radius and  $p = CN$ . A strip of glass graduates throughout its entire length was applied to aperture so that its end came into contact with the edge of the zinc plate and the value of  $p$  was estimated to the tenth of a millimeter.

The tuning forks used consisted of a set of 13 forks giving a tempered chromatic scale within the range of  $c_1$  to  $c_2$ . The number of vibrations of these forks had been previously determined approximately in comparison with a set of standard forks made by Koenig. For lower notes, Koenig's forks giving Sol,  $Mi_2$ , and  $Ut_2$  were employed.

First the air column within the pipe was adjusted to a desired length  $l$ . The different forks were successively brought

near the aperture, the zinc plate was so adjusted that the resonance was maximum and then the corresponding value of  $p$  was measured. Next the length of the air column was changed and the procedure was repeated. The result of these experiments gave the relation between the dimensions of the embouchure and the proper pitch of the resonator for different lengths of the air column. The results are given in Fig. 3 in which the abscissa is the number of vibrations of the resonator and the ordinate is the fourth root of the area of the aperture  $\sigma$ . From the diagram, it will be seen that:

1. The curves  $n$  to  $\sigma^{\frac{1}{4}}$  for different values of  $l$  seems to converge toward the origin with a slight curvature.

2. When the length of the air column becomes comparable with its diameter, as for  $l=5.23$  cm., the number of vibrations is nearly proportional to  $\sigma^{\frac{1}{4}}$ .

3. The greater the length of the air column, the slower the pitch rises with the increase of the aperture.

4. The narrower the area of the aperture of the embouchure the greater is the ratio  $\frac{\partial n}{\partial \sigma^{\frac{1}{4}}}$ .

Care was duly taken not to bring the tuning fork so near to the aperture of the embouchure as to affect the natural pitch.

The effect of the moisture in the air column was calculated and found to be insensible within the required range of accuracy.

The pitch of a simple resonator having its three dimensions comparatively smaller than the wave length and communicating with the external atmosphere by a small opening in its surface, has been investigated by many eminent physicists. Helmholtz<sup>1)</sup> obtained theoretically for a circular aperture,

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1) Helmholtz, Crelle, Bd. LVII. 1-72. 1860.

$$n = \frac{a\sigma^{\frac{1}{2}}}{2^{\frac{1}{2}}\pi^{\frac{5}{2}}S^{\frac{1}{2}}},$$

where  $S$  is the volume and  $a$  the velocity of the sound wave in air. Sondhauss<sup>1)</sup> obtained experimentally

$$n = 52400 \sigma^{\frac{1}{2}} S^{\frac{1}{2}} \quad (\text{length in mm.})$$

These results have been discussed by Lord Rayleigh<sup>2)</sup> in his classical paper on resonance. On the other hand, the correction for the open end of a cylindrical resonator has been treated both experimentally and theoretically by many physicists,<sup>3)</sup> beside the worthies above quoted. The present experiments furnish in some measure the intermediate stage of transition from the first case to the second. As will be seen from the above result, when the length of the air column is small, the pitch is nearly proportional to  $\sigma^{\frac{1}{2}}$  and also nearly so with  $l^{-\frac{1}{2}}$  or  $S^{-\frac{1}{2}}$ ; and when the area of the aperture gradually approaches a complete circle, the curves  $n$  to  $\sigma^{\frac{1}{2}}$  tend to the values given by the previous results for the open pipe.

It is an established fact that for a similar resonator, the pitch is inversely proportional to its homologous dimensions. Hence, the above results may be applied to other pipes with different diameters, if  $n$  and  $l^{-1}$  be multiplied by the ratio (the diameter of the glass pipe above experimented on / the diameter of the other pipe) and  $\sigma^{\frac{1}{2}}$  by (the same ratio).<sup>—1</sup>

1) Sondhauss, Pogg. Ann. LXXXI. pp. 245, 357, 1850.

2) Rayleigh, Phil. Trans. CLXI. pp. 77-118.

3) Poisson, Mem. de l'Acad. des Sci. 1817, II, 305. Savart, Ann. d. Chim. t. XXIV, 1823. Hopkins, Cam. Phil. Trans. V, 1838. Quet, Journ. d. Liouville, XX, 1, 1855. Wertheim, Ann. d. Chim. et Phys. (3), XXIII, 434; and XXXI, 385, 1848-51. Zaminer, Pogg. Ann., XCVII, 183, 1856. Gripon, Ann. d. Chim. III, 384, 1874. Rayleigh, Phil. Mag. (5) III, 456. Bosanquet, ibid IV, 291, 1877; and VI, 63, 1878. Koenig, Wied. Ann. 569, 1881. Blaikley, Phil. mag. (5) VII, 339, 1879.

Helmholtz, Crelle, Bd. 57, 1860; Gesammelte Abhandlungen Bd. I.

The effect of the thickness of the pipe or of the plate is very small, provided it is very small in comparison with the wave length. The relation above obtained is, therefore, applicable also to the case of the *syakuhati* as shown in the latter part of this paper.

### 3. Lateral Openings.

Lord Rayleigh<sup>1)</sup> in his paper on resonance, has suggested a method for the theoretical treatment of the lateral openings of wind instruments. However, as far as I am aware, no further result either theoretical or experimental has been published. The necessity of investigating the functions of the lateral openings for the explanation of the phenomena connected with the *syakuhati*, led me to undertake a series of experiments which I shall now describe.

A cylindrical pipe was made of a zinc plate, 0.5 mm. thick, with an inner diameter of 4.0 cm. and a length of 1 m. A long scale printed on paper was attached to the side of the cylinder. A cylindrical tank with a depth of over 1 m., was filled with water in which the cylindrical pipe was inserted vertically so as to vary the length of the air column inside the resonator when the pipe was raised or lowered by hand. Lateral holes of different diameters were made in the side of the pipe at different positions. For different positions of the holes, the lengths of the air columns were determined which give respectively the maximum resonance for different tuning forks.

For the degree of accuracy required for the present purpose, the raising or lowering of the pipe could conveniently be done with one hand, while the other hand held the fork near the

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1) Rayleigh, loc. cit.

opening. Arrangements which in the earlier part of the experiment had been used for guiding the motion of the pipe and for reading its height were afterward dispensed with. The verticality of the pipe was approximately secured by a straight brass rod fixed parallel along the side of the pipe at a distance of 2.5 cm, this rod being held in contact with the side of the tank during the raising and lowering of the pipe.

Holes which had to be covered, were closed air-tight with curved plates of zinc closely fitting the side of the pipe, and sealed with a kind of tallow. The slight irregularity on the inner wall of the pipe due to the closing of the hole in this way, was found to affect the velocity of sound within the pipe in no sensible degree.

The results of the experiments are summarized below:

a) Correction for the open end.

First, the correction of the length due to the open end only was determined in the usual manner, before any holes were made. The results gave  $0.42 R$  for the mean value, where  $R$  is the sectional radius of the pipe.

b) One circular hole.

In Figs. 4, 5 and 6, the relation is given between the distance  $d$  of the center of the hole from the open end and the total length  $L$ , from the open end to the water surface which gives the maximum resonance for different tuning forks. The difference of the ordinate between the curve and a straight line through the origin making an angle of  $45^\circ$  with the axes, gives the distance  $l$  of the center of the hole from the water surface. The value of  $\frac{\lambda}{2} - l = d$  where  $\lambda$  is the wave-length corresponding to the note, may be considered as the correction due to the lateral opening. It will be seen that the correction increases first



slowly with  $d$  and then rapidly when  $d$  approaches the half wave length. The rapidity of the increase of the correction  $\alpha$  with  $d$ , depends on the width of the lateral hole. Fig. 7. shows the relations between  $d$  and  $\alpha$ , for  $c_1$ , corresponding to three different values of the diameter of the hole  $r$ . The curves have very long inflexions so that when  $d$  is neither very small nor near the half wave length, they may be regarded as approximately straight lines apparently converging to a point on the axis of  $d$ .

For different notes with different wave lengths, it was found that if the curves be drawn for different notes representing the relation of  $\alpha$  and  $\frac{d}{\lambda}$  (instead of  $d$ ), they coincide with each other very closely except when  $\frac{d}{\lambda}$  is nearly  $\frac{1}{2}$ . This is true for holes with different areas.

When  $d$  becomes greater than  $\frac{\lambda}{2}$ , the relation is quite similar to what it would be if the pipe were cut off at a distance equal to  $\frac{\lambda}{2}$  from the open end. If the upper end of the pipe be perfectly closed by a rigid plate, the results are similar to those obtainable in case the pipe were prolonged by a length  $= \frac{\lambda}{4} - 0.4 R$  and the rigid plane were removed. If, again, the open end be partially closed with a plate having a circular hole, the case is quite similar to what it would be if the tube were produced by  $\frac{\lambda}{4} - c$  where  $c$  is the correction of the length due to that partial opening. The latter fact has been verified experimentally with several mouth plates, with different diameters, the corrections due to which had been previously determined. Thus,  $\alpha$  is periodic with respect to  $\frac{d}{\lambda}$ , with the exact period of  $\frac{1}{2}$ .

c) Several holes.

When more than one hole is made, the case becomes much complicated, since the different combinations of holes produce a great number of cases which must be investigated independently.

From the results of the experiments, we may infer generally that the correction  $\alpha$  for any one hole is diminished by making another hole nearer the open end, and that the diminution increases with the width of the second hole and with its approach to the first hole. In Figs. 4, 5 and 6, the dotted lines give the value of  $l$  when a similar hole is made at  $s$  cm. from the first opening. It will be seen that for the diameter of holes = 1.8 cm., the effect of the second hole is to make the curve  $\alpha$  to  $\frac{d}{\lambda}$  almost parallel to the axis of  $\frac{d}{\lambda}$ .

The correction  $\alpha$  diminishes almost uniformly with the decrease of the distance separating the two holes; and the rate of the diminution increases with the diameter of the second opening or with the number of further openings if such be present; but it is nearly independent of the distance of the first opening from the open end. The relation may be seen from the following tables:—

TABLE I.

Diameter of holes=5 mm.

Distances of holes from the open end=0.7, 6.75, 11.75, 16.75  
and 21.75 cm.

$L$  = Length of air column for maximum resonance, in cm.  
 $a$  = Quarter wave length minus the distance between the  
 closed end and the open hole nearest to it, in cm.  
 o : opened.  
 x : closed.

Positions of Holes closed end $\longrightarrow$ opened end					$t=15^{\circ} C$			
					$c_1 : \frac{\lambda}{4} = 31.9 \text{ cm.}$		$f_1^{\#} : \frac{\lambda}{4} = 22.5 \text{ cm.}$	
					$L$	$a'$	$L$	$a'$
1	o	o	x	x	42.6	11.1	32.4	11.8
2	o	x	o	x	41.5	12.2	30.9	13.3
3	o	x	x	o	40.7	13.0	29.5	14.7
4	o	x	x	x	39.9	13.8	28.4	15.8
5	o	x	x	x	39.8	13.9	28.3	15.9
6	o	o	o	x	43.8	9.9	33.3	10.9
7	o	x	o	o	41.9	11.8	31.5	12.9
8	o	x	x	o	40.8	12.9	29.7	14.5
9	o	o	o	o	43.9	9.8	33.8	10.4
10	o	x	o	o	42.0	11.7	31.6	12.6
11	x	x	o	o	35.5	8.2	25.8	8.4
12	x	x	o	x	34.6	9.1	24.9	9.3
13	x	x	o	x	34.5	9.2	24.8	9.4

TABLE II.

Diameter of holes=1 cm.

Distances of holes from the open end=0.8, 6.75, 11.75, 16.75,  
21.75 and 31.75 cm.

$t=15^{\circ} C$				
Positions of Holes closed end $\longrightarrow$ opened end	$c_1 : \frac{\lambda}{4} = 31.9 \text{ cm.}$		$f_1^{\#} : \frac{\lambda}{4} = 22.5 \text{ cm.}$	
	$L$	$a$	$L$	$a$
1 O . O X X X X	55.4	8.3	44.8	9.4
2 O . X O X X X	54.8	8.9	43.5	10.7
3 O . X X X O X	53.2	10.5	39.2	15.0
4 O . X X X X X	52.0	11.7	34.7	19.5
5 X . O O X X X	46.8	6.9	37.1	7.1
6 X . O X O X X	45.9	7.8	35.8	8.4
7 X . O X X O X	45.1	8.6	34.8	9.4
8 X . O X X X O	44.7	9.0	33.8	10.4
9 X . O X X X X	44.5	9.2	33.6	10.6
10 X . O O O X X	47.4	6.3	37.7	6.5
11 X . O X O O X	46.2	7.5	36.1	8.1
12 X . O X X O O	45.3	8.4	34.9	9.3
13 X . O O O O X	47.6	6.1	38.1	6.1
14 X . O O X O X	47.1	6.6	37.3	6.9
15 X . X O O X X	42.5	6.2	32.7	6.5
16 X . X O X O X	41.6	7.1	31.8	7.4
17 X . X O X X O	40.9	7.8	30.8	8.4
18 X . X O X X X	40.9	7.8	30.6	8.6
19 X . X X O O X	37.8	5.9	28.3	5.9
20 X . X X O X O	36.9	6.8	27.4	6.8
21 X . X X X O O	33.8	4.9	24.3	4.9

TABLE III.

Diameter of holes=1.8 cm.

Distances of holes from the open end=11.7, 21.7, 31.7, 41.7,  
and 51.7 cm.

						$t=15^{\circ} C$			
Positions of Holes						$c_1 : \frac{\lambda}{4} = 31.9 \text{ cm.}$		$f_1^{\#} : \frac{\lambda}{4} = 22.5 \text{ cm.}$	
closed end $\longrightarrow$ opened end						$L$	$a$	$L$	$a$
1	o	o	x	x	x	79.6	4.0	—	—
2	o	x	o	x	x	78.9	4.8	68.3	5.9
3	o	x	x	o	x	78.1	5.5	64.9	9.3
4	o	x	x	x	o	77.2	6.4	—	—
5	o	x	x	x	x	73.5	10.1	—	—
6	x	o	o	x	x	69.7	3.9	59.8	4.4
7	x	o	x	o	x	69.1	4.5	58.8	5.4
8	x	o	x	x	o	68.3	5.3	56.4	7.8
9	x	x	o	o	x	59.8	3.8	50.0	4.2
10	x	x	o	x	o	59.1	4.5	49.0	5.2
11	x	x	x	o	o	49.8	3.8	40.1	4.1

For this value of the diameter of holes, the effect of a third hole is almost insignificant.

If the second hole be wider than the first, the rate of diminution of  $a$  with the decrease of the distance between two holes is greater than in the case where the two holes are of an equal area. This is shown by the following table when compared with Table I.

TABLE IV.

○ : diameter = 0.5 cm.

⊙ : „ = 1.0 cm.

Distances of holes from the open end = 0.8, 6.75, 11.75, 16.75 and 21.75.

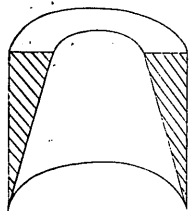
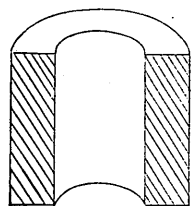
Positions of Holes closed end → opened end	$t = 15^\circ C$			
	$c_1 : \frac{\lambda}{4} = 31.9 \text{ cm.}$		$f_1^\# : \frac{\lambda}{4} = 22.5 \text{ cm.}$	
	$L$	$a$	$L$	$a$
○ ⊙ × × ×	44.5	9.2	34.5	9.8
○ × ⊙ × ×	42.9	10.8	32.5	11.8
○ × × ⊙ ×	41.3	12.4	30.5	13.8
○ × × × ⊙	39.9	13.8	28.6	15.7

#### 4. Effects of Knots.

Lord Rayleigh<sup>1)</sup> proved that any slight contraction or expansion of the section of a cylindrical resonator affects more or less its natural pitch and that a broadening at the loop or a contraction at the node raises the natural pitch. The case treated by him is confined to the case where the variation of the section is very gradual. In the case of the *syakuhati*, the change of the section due to the knots is rather abrupt though small in amount. In order to test the effects due to diaphragms placed in a cylindrical resonator, the following simple experiments

1) Rayleigh, Theory of Sound. II.

were carried out. The cylindrical glass pipe used in the previous experiment for the effect of the aperture of the embouchure was fixed horizontally. The length of the air column inside the pipe was adjusted by means of a wooden piston around which a sheet of cloth was wound so that it fitted tightly to the inside of the pipe. Diaphragms were made of wooden cylinders of different lengths bored with cylindrical or conical passages of different calibres. Their lateral sides were covered by velvet in order to secure close contact with the interior of the glass pipe. Each of them was placed in the resonator successively



at different distances from the open end. The tuning forks of the series used in the previous experiments, were successively brought near the open end and the lengths of the tube giving the maximum resonance were determined.

First, the diaphragms with cylindrical passages of different diameters, were tested. The results of the experiments are given in Figs. 8, 9, and 10 in full lines, in which the abscissa is the distance of the middle section of the diaphragm from the open end, and the ordinate is the length of the air column measured from the open end to the piston. Horizontal dotted lines show the length of maximum resonance when no diaphragm is present. The difference of the ordinate between a curve in full line and the corresponding horizontal dotted line gives the correction of the length due to the corresponding combination of the diaphragm and the tuning fork. It will be remarked :

- a) That the curves for different notes are nearly parallel ;
- b) The the correction is negative when the diaphragm is

near the node, is null at a certain distance from it, and thence increases almost proportionally with its distance from the node.

c) That the correction increases with the decrease of the sectional area of the passage, first slowly and then rapidly, as is also shown in the following table :

TABLE V.

Length of the diaphragm=1 cm.

Diameter of the passage.	Correction due to the diaphragm when its end is at the open end.	
	$c_1$	$c_2$
4 cm.	0.0 cm.	0.0 cm.
3	1.3	1.3
2	4.2	3.3
1	15.4	9.1

The intensity of resonance falls rapidly with the decrease of the diameter of the passage, when it becomes small. When the passage is narrow, the pipe is rather to be regarded as a system of two resonators communicating with each other by a narrow passage. In such a system, two modes of the vibration are possible. The one mode which was experimented with above is that in which the phase of the air motion is everywhere nearly the same. The other mode, in which the motions in the two parts are opposite, however, was entirely left out of consideration. Indeed, when the intermediate passage becomes narrow, the former mode becomes faint, while the latter becomes predominant. This fact may easily be shown by experiments. For the present problem,



however, we confine our study to the former mode exclusively. The latter mode will, I hope, form the subject of a future communication.

The results when a conical passage was used, are given in Figs 8, 9, and 10, in broken lines; the diameter given there is that of the narrower end, the wider one being always 4 cm. i.e. equal to the inner diameter of the pipe. Here, again, the abscissa is the distance between the open end and the middle section of the diaphragm. The results are quite unaltered if the direction of the conical channel be inverted. It will be seen from the figures:

a) That the correction due to the diaphragm is about 0.4 times less than that of the corresponding cylindrical channel whose sectional diameter is equal to the diameter of the narrower end of the conical channel.

b) That the full line and the corresponding broken line intersect each other at a point near the corresponding horizontal dotted line. This shows that, where the effect of the diaphragm is null, its form and size are immaterial.

c) That the straight line joining these points of intersection for different notes, is directed toward the origin. This shows that the position at which the effect of the obstacle is null, is given by the ratio of the distance from the piston or the open end to the wave length of the note.

Lastly, the effect of the length of the diaphragm was studied. The result is shown in Fig. 11. It will be noticed that the correction increases with the length of the channel. Though in this case the length of the diaphragm ranges from 5 to 1 cm., the different curves are nearly concurrent to a point on the corresponding dotted line, if the abscissa be taken proportional

to the distance between the middle section of the diaphragm and the open end of the glass pipe.

Another way of studying the effect of diaphragms is as follows. Inside an ordinary organ pipe a diaphragm is so inserted that its position may be adjusted in any desired way; the pipe is blown by means of a regulated bellows; and the pitch of the pipe for different positions of the diaphragm is determined. The organ pipe used in my experiment was a wooden one with a rectangular section, giving  $\alpha_1$  for the fundamental tone. The diaphragm was made of wood, fitting tightly in the inside of the pipe and perforated with a channel having a rectangular section. The lateral side of the diaphragm was covered with cloth in order to secure close contact with the inner wall of the pipe. The diaphragm could be brought to any position by means of two thin rods of steel which were fixed to the diaphragm diagonally opposite to each other. If the diaphragm is gradually pushed into the pipe while it is being blown with a constant pressure, the pitch of the note gradually rises till a maximum is attained at the node of the pipe; whence the pitch falls gradually with the further position of the diaphragm. The results of the experiment are quite analogous to those in the former experiment.

For the case when the section of a nearly cylindrical pipe varies slightly, Rayleigh obtained

$$\Delta l = \int_0^l \cos \frac{2\pi x}{l} \frac{\Delta S}{S_0} dx$$

where  $\Delta l$  is the correction of the length due to the irregularity;  $l$  the length between the consecutive loop and node;  $\Delta S$  the small variation of the section given as a function of  $x$  measured from the node along the length of the pipe; and  $S_0$  the mean section.

This relation has been obtained on the supposition that the velocity of flow in every transverse section is uniform. The assumption does not hold in the cases investigated, since the abrupt change of the section at both ends of the diaphragm produces an irregular flow of the air. It will be interesting, however, to test the above relations for the present case.

Let  $\Delta S = \text{const}$ , between  $x = \xi + a$  and  $\xi - a$ , and elsewhere  $= 0$ . Then, we have

$$\Delta l = \frac{l}{\pi} \frac{\Delta S}{S_0} \cos \frac{2\pi\xi}{l} \sin \frac{2\pi a}{l}.$$

For  $\Delta l = 0$ , we obtain  $\xi = \frac{1}{4}l$ . This is nearly the case in Figs. 9 and 10.

If  $\xi = l$ ,

$$\Delta l = -\frac{l}{\pi} \frac{\Delta S}{S_0} \sin \frac{2\pi a}{l}.$$

Therefore, if  $a = \text{const.}$ ,

$$\Delta l \propto \Delta S \quad \text{or} \quad \propto (R-r)^2$$

where  $R$  is the radius of the cylinder and  $r$  that of the channel. This is verified qualitatively in the table given in p. 24.

Comparing the above formulae with the results given in Figs. 8, 9, and 10, we see generally that the actual values of  $\Delta l$  are far greater than the theoretical values, the discrepancy increasing with the decrease of the radius of the passage. This shows that the disturbance due to the end of the diaphragm is considerable.

## APPLICATIONS OF THE RESULTS OF THE EXPERIMENTS TO THE SYAKUHATI.

The results of the present experiments may be applied to the case of the *syakuhati* in the following ways:—

The position of the node when all the lateral openings are closed, is easily found, since the lower end must correspond to the loop, provided the usual correction for the open end is made. When the embouchure is adjusted so that the note is  $c_1^\sharp$ , for this position, the distance  $N$  of the node from the mouth must be

$$N = L + 0.8 R - \frac{\lambda}{4}$$

where  $L$  is the total length of the *syakuhati* = 49.2 cm.;  $R$  the inner radius = 1 cm.;  $\frac{\lambda}{4} = 30.1$  cm. ( $t = 15^\circ C$ ).

$$\therefore N = 9.9 \text{ cm.}$$

Now, as already mentioned, Fig. 3 may be reduced to the case of a similar cylindrical resonator with its sectional diameter equal to that of the *syakuhati*. Since in the present experiment, the ratio of the diameter of the glass pipe used to the sectional diameter of the *syakuhati* is nearly 2, the value of  $n$  in the figure was multiplied by 2 and  $l$  was divided by 2. From the figure thus reduced, was found the value of the ordinate for which  $\frac{\lambda}{4} - l$  for  $c_1^\sharp$  is 9.9 cm. For this value of the ordinate, a curve giving the relation  $l$  to  $n$  was drawn, whence the correction corresponding to any other note could be obtained. In this way,  $N$  for any position of the holes can be found, if we have only determined the number of vibrations of the notes corresponding to that position. We have

$$N = \frac{\lambda}{4} - \left( \frac{\lambda}{4} - l \right) = l.$$

$N + \frac{\lambda}{4}$  from the embouchure gives the position of the virtual loop. The distance of this apparent loop beyond the open hole is to be regarded as the correction due to the opening.

The result of the calculation for a number of positions is tabulated below :

Nos. of Positions (see p. 8-9)	$\frac{\lambda}{4}$	$N$
1	30.1	20.0
2	25.5	16.8
3	23.3	14.7
4	22.8	14.3
5	20.8	12.6
6	20.4	12.1
8	20.0	11.8
9	19.0	10.7
10	18.3	10.2
12	17.8	9.8
16	17.2	9.4
17	—	—
18	16.8	8.9
20	16.2	8.2
24	15.7	7.8
32	14.6	7.5

The fact that in the *syakuhati*, the change of the *interval* of the notes, but not the difference of the *number of vibrations* due to a given change in the embouchure, is nearly equal for different positions of the lateral openings, corresponds to the results of the experiment with the glass pipe viz., that the longer the air column, the steeper is the curve  $n$  to  $\sigma^{\frac{1}{2}}$ .

The results of the effects of lateral openings, if combined with those of the aperture of the embouchure, enable us to calculate approximately the pitches of the notes corresponding to different positions of the finger-holes.

Within the compass of the fundamental notes of the *syakuhati*, the correction due to the lateral openings, is represented nearly by

$$a = f(r) \left( \frac{d}{\lambda} + e \right),$$

where  $e$  is constant and  $f(r)$  is a function of the radius  $r$  of the lateral openings. From the curve I in Fig. 7 for which the ratio  $\frac{r}{R}$  is equal to that in the *syakuhati*,

$$a = 12.8 \times \left( \frac{d}{\lambda} + 0.047 \right) \text{ cm.}$$

Again from Fig. 3, the correction due to the embouchure is given by

$$a' = A - m(n - n_0) = 10.8 - \frac{2}{250}(n - 250)$$

$$= 12.8 - \frac{272}{\lambda} = B - \frac{k}{\lambda}$$

now,  $\frac{\lambda}{2} = l + a + a' = l + f(r) \left( \frac{d}{\lambda} + e \right) + B - \frac{k}{\lambda}$

$$\therefore \lambda^2 - 2[l + ef(r) + B]\lambda - 2[f(r)d - k] = 0$$

$$\lambda = \{l + B + ef(r)\} \left\{ 1 + \sqrt{1 + \frac{2[f(r)(L - l) - k]}{[l + B + ef(r)]^2}} \right\}$$

In the *syakuhati*,

$$\lambda = (l + 13.4) \left[ 1 + \sqrt{1 + 2 \cdot \frac{357 - 12.8l}{(l + 13.4)^2}} \right]$$

For an example :—

Position	$l$	$\frac{\lambda}{2}$ <i>calc.</i>	$\frac{\lambda}{2}$ <i>obs.</i>
No. 9	23.4	37.7	37.7
No. 2	38.2	50.1	50.6

The variation of the sectional diameter of the pipe due to knots, is at most 1/20 of the general diameter. For the fundamental tones of the different positions, the effects of such a small irregularity would be very small, as may be seen from the results of experiments on the effects of the diaphragm. The effect, however, increases when the irregularity becomes considerable in comparison with the wave length, since the inclination of the curves in Figs. 8, 9 and 10 becomes great with the decreasing wave length. This probably accounts for the change of the timbre due to the knots.

A direct experiment on the effect of a small change of the section was also made. Several glass tubes with equal lengths of 23 cm., and equal general sections of 2.2 cm., except at a place where they contracted or broadened by 1 or 2 mm., were attached to the embouchure of a cylindrical organ pipe. They were blown with a bellow under a constant pressure, which was measured by a water manometer. The frequencies of the different pipes were compared with a proper tuning fork by counting the number of beats. Whether the note of a pipe was higher or lower than that of the fork, could easily be decided by slightly varying the pressure of the air; if the increased pressure decreases the number of the beats, the pitch of the pipe is a little lower than that of the fork and *vice versa*. It was found that the effect of such a small irregularity is very

small, provided that it is not situated at the open end of the pipe. For the note  $c_1$ , the variation of  $n$  was at most 3 when the above mentioned irregularity was situated at above 4 cm. from the open end.

The effect of the slight general conicality<sup>1)</sup> on the natural pitch, is known to be of a second order of magnitude.

The function of the *gorobusi* seems to be to lower the note for position No. 2, by increasing the resistance of the channel. If the knot is absent, the note will be a little too high and the interval of the note above the gravest note will be too great. Besides, it is suspected that the strength of the pipe due to this knot has something to do with the tone of the pipe. This is a question still to be studied.

The irregularity of the overtones remains to be explained. For most of the fundamental tones, the vibration of the air in the pipe is chiefly in the part of the pipe above the open hole nearest to the embouchure; the principal part of the energy of the vibration is transmitted to the external air from the lateral hole or holes. This is shown by inserting in the lower end of the pipe a glass tube communicating with a manometric capsule. The disturbance of the flame is very small compared with the case when the end of the glass tube is driven into the upper part of the pipe or when it is inserted in the lateral hole. However, when an overtone is excited which is higher than the octave of the corresponding fundamental note, the manometric flame communicating with the lower end of the pipe, is set in a forcible vibration, showing that for this mode, the lower part of

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1) Rayleigh, Theory of Sound, II, 115.  
Boutet, Ann. d. Chim. XXI, 150, 1870.  
Blakley, Phil. Mag. VI, 119, 1878.



the pipe plays an important part in the production of the note. Indeed, for overtones, the distance between the lower end and the holes approaches the half wave lengths of the notes, so that the lower part may form a resonator whose pitch is near that of the upper part. Thus the pipe, as a whole, forms a communicating system of two resonators. The complete explanation of the phenomena may, therefore, be made only after the investigation of such a multiple system of resonators, has been fully made. However, a qualitative explanation is possible for a number of cases, as in the following.

In position No. 5, the virtual length of the pipe above the open hole is nearly equal to the whole wave length of the note  $a_2^{\#}$  while the lower half is a little longer than the half wave length of the same note. Therefore, for this note, the vibration of the air takes place within the pipe in such a way that very near the open hole an actual loop is produced and only a small portion of the energy escapes from the lateral opening. This is verified by the experiment, since if the open hole be closed while the pipe is being blown, the general mode of the vibration remains nearly unaltered, only the pitch is slightly lowered. Indeed,  $a_1^{\#}$  corresponds nearly to the second overtone of position No. 1. In a similar way, in the first overtones for the positions Nos. 18, 19, 20, 23, 24, 25, etc., the back hole approximately corresponds to the loop of the third overtone of the position No. 1. Therefore, for these positions in which holes near the nodes of that mode are closed, this note is liable to be produced.

In position 17, the fundamental tone is very high if compared with others such as Nos. 18, 19, etc. In this position, no energy escapes from the back hole, so that there is no change

in the note, if that hole be closed; the position is really equal to position No. 1.

The intermediate overtone  $f_2$  in position 18, is related to the position No. 2, in the same way that No. 17 is to No. 1.

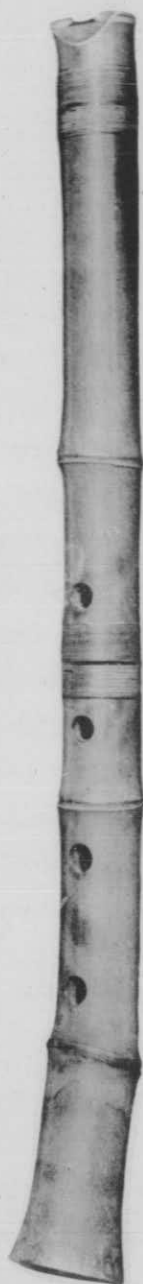
The intermediate overtone  $d_2+$  is due to the lower half of the pipe.

The probable defect of the instrument, lies in the too wide interval of the notes between positions Nos. 1 and 2. This inconvenience may be avoided if an additional hole be opened below the *gorobusi*, corresponding to the little finger of the right hand. I have calculated the position of this side hole for the note  $d_1$ , for the *syakuhati* investigated, and obtained 6.0 cm. for its distance from the open end. On opening the hole, the desired pitch was obtained, and moreover, the overtone of the new hole filled up the gap for the missing  $d_2^*$ . Another convenience attained by this hole is that, by opening it, the irregularity of the overtones is removed for most cases, since it divides up the lower part of the pipe into short halves and thereby hinders the interference due to that part. The best position of the new hole, however, must be determined rather by convenience in playing. From this point of view, a little higher position of the hole, would be recommendable, so that the end of the little finger might cover the hole without much effort.

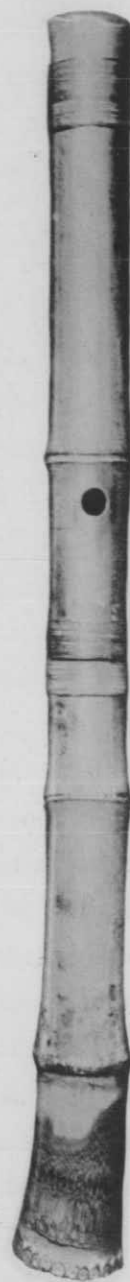
My best thanks are due to Prof. A. Tanakadate and Prof. H. Nagaoka who have favoured me with kind encouragement and useful suggestions, during the course of my investigations, and also to Mr. R. Uehara who kindly placed his instrument at my disposal for photographic reproduction.

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*Fig. 1.*



*Fig. 2.*



*Syakuhōki.*

*Fig. 1, Front view. Fig. 2, Back view.*

Fig. 8.

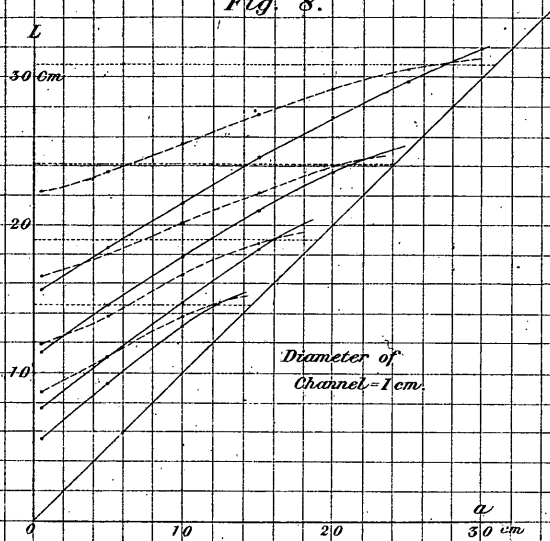


Fig. 10.

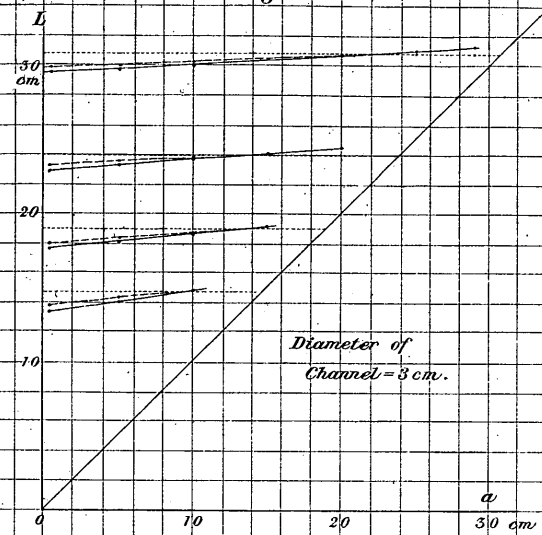


Fig. 9.

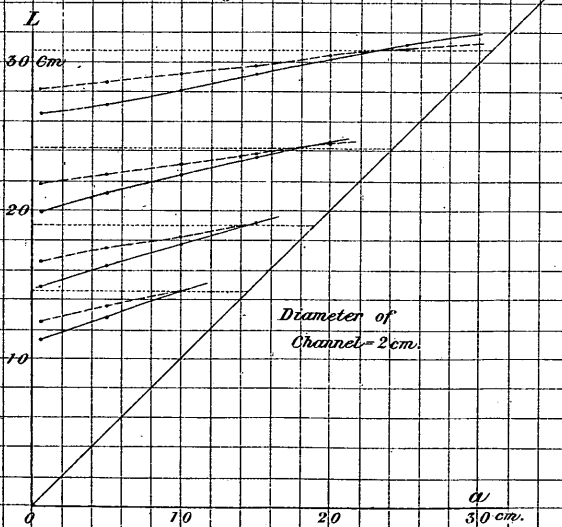


Fig. 11.

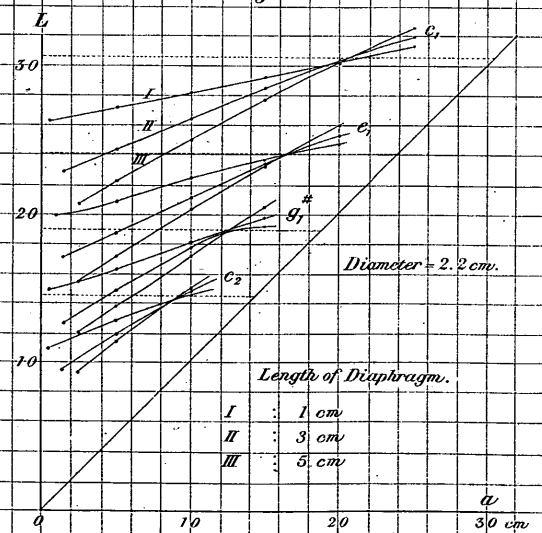


Fig. 3.

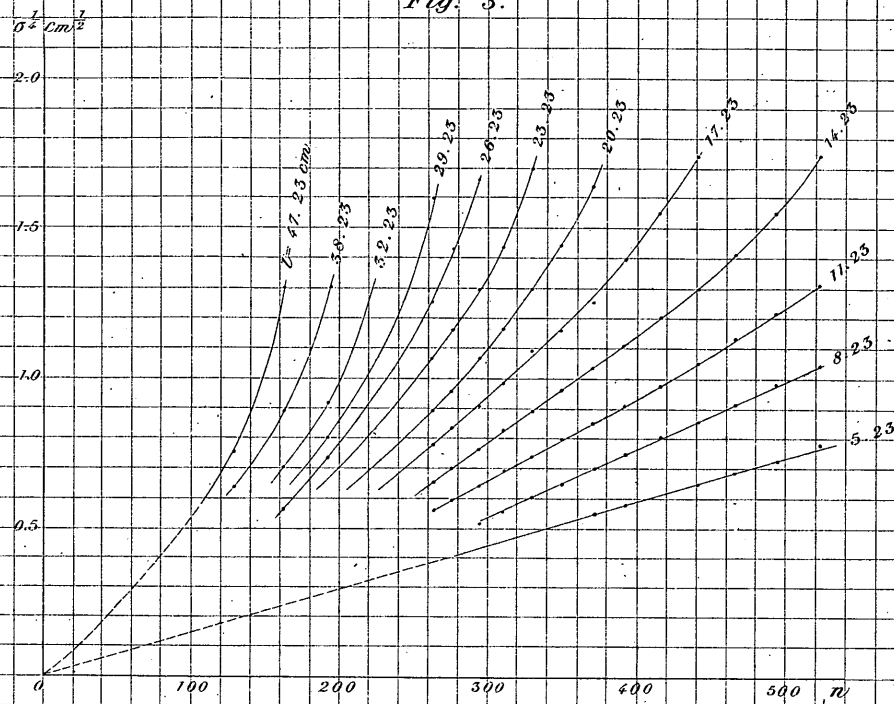


Fig. 4.

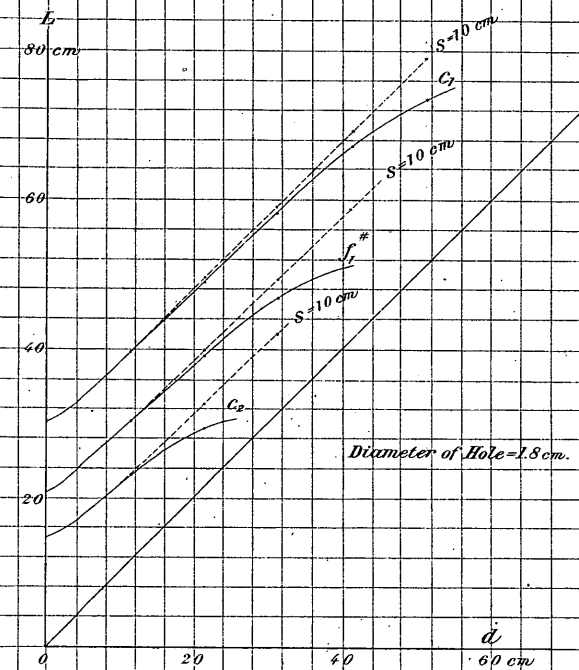


Fig. 5.

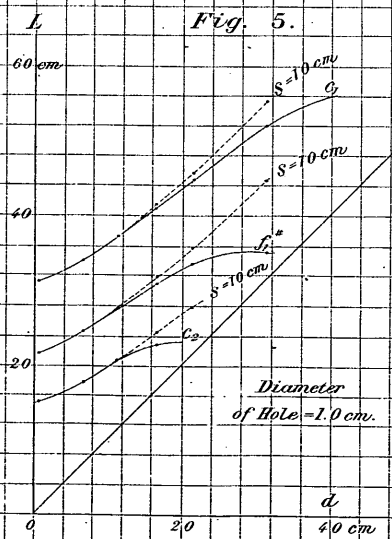


Fig. 6.

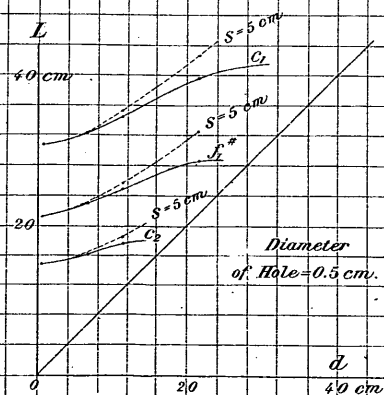


Fig. 7.

