THE ACTION OF THE BOW IN STRINGED INSTRUMENTS.

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SYNOPSIS.

Motion of Points of a String near the Bowing Region.—Shadows of a small section of the horizontal string and of pins stuck in the bow were thrown on a vertical slit back of which a piece of photographic paper was moved. The resulting prints each show a saw tooth line due to the string, crossed by inclined straight lines due to the pins. Experiments were made with the bow one seventh, one tenth and one fourteenth of the length of the string from one end. In every case the speed of the points of the string is proportional to the distance from the near end. The point with a speed equal to that of the bow is called the zero point. With strong slow bowing the zero point is at the outer edge of the bow, but with lighter or faster bowing the zero point may be 2 cm. or more nearer the middle of the string. While the "wolf note" is sounding the zero point oscillates periodically with the beating; it may be stopped by increasing the pressure. The amplitude at the outer edge of the bow is proportional to the speed of the string at that point and hence will change as the zero point is shifted by variations of pressure, even when the bowing speed is constant.

INTRODUCTION.

HELMHOLTZ, referring to the particular case in which the motion of the bowed point is represented by two step zig-zag, remarks¹ that the velocity of the string, in the forward motion "appears to be equal to that of the bow." In later treatises² the velocity of the forward motion is stated to be equal or about equal to that of the bow. Recently Professor Raman has made an experiment³ with his vitrograph (see Fig. 1) and has shown that the velocity of the bow is exactly equal to the velocity of the bowed point of the string in its forward motion. His conclusion was based on the fact that the record of the pin attached to the bow and that of the string are absolutely parallel. But we should note that the photograph taken by him does not represent the motion of the bowed point, but of one a little away from it.

Now in practice a bow is never applied at a point. Thus in dealing with the problem we are to take into account the length of the bowed region, which is generally about 1 cm. long. This brings us at once to the question as to which point of the string in the bowed region, if any, has the same velocity as the bow. These problems raised by Prof.

¹ Sensations of Tone, p. 83.

² Lord Rayleigh's Theory of Sound, Vol. 1, and Barton's Text book of Sound, Art. 261.

³ The Dynamical Theory of the Motion of Bowed Strings, Bulletin No. 11 of Indian Association.

Raman in his monograph¹ are solved by the following experiment made by the writer.

I am deeply indebted to Professor Raman at whose suggestion I took up the work.

EXPERIMENT.

The apparatus is shown in Fig. 1. An arc placed in front of the apparatus provides the necessary illumination. A photographic paper contained in a dark slide is arranged to slide in grooves within the wooden box, parallel to the string. A number of pins are fixed to the bow transversely so that when bowed near the slit *S*, the images of the pins moving with the velocity of the bow, fall on the photographic paper inside the vitograph. The transverse vibration of the string is at the same time recorded on the photographic paper. It is therefore possible by this method to get simultaneous records of the motion of the bow and of the vibration of a point on the string in the neighborhood of the bowed region.

Fig. 1.

Exact determination of the point on the string whose vibrations have been recorded, is made by the following very simple method. A pin is held against the string and moved along it until its image falls on the slit. Vibrations of this point of the string have obviously been recorded. The distance of this point from one end of the string (here it is the remoter one) is measured with a meter scale. It should be noted that the position of the arc should not be changed during the experiment.

The inner and the outer limits² of the bowed region are marked with ink on the string. And by moving the slit to different positions, simultaneous records of the velocity of the bow and vibrations of different points of the string are taken. The bowing pressure has been made just sufficient to elicit a steady tone with pronounced fundamental, the velocity of the bow being kept constant as far as practicable. Three sets of records have been taken for three different positions of the bow.

¹ Bulletin No. 15, Indian Association for the Cultivation of Science.

² The inner limit or the limit nearer the nearer end of the string.

Fig. 2.

Records obtained are somewhat like that in Fig. 2. When the slit is placed anywhere between the inner edge of the bowed region and the nearer end of the string, angle β is always greater than angle α as in Fig. 2. When, however, the slit is on the other side of the bow, *i.e.*, away from the outer edge of the bowed

region, β is generally less than α .

The ratios of the velocities of the string and the bow have been determined accurately from the records by measuring the tangents of the angles β and α with a moving microscope (moving in two perpendicular directions) and taking their ratios.

The results of these measurements are given in the following table:—

TABLE I
Length of the string is 53.6 cm.

	Bowed Region between.	Observed at	Vel. of String/Vel. of Bow Mean.
A.	45.55 cm.—46.45 cm.	42.1 cm.	1.358
		43.65 "	1.133
		47.40 "	.667
		49.20 "	.484
B.	47.65 cm.—48.55 cm.	48.90 "	.781
		49.40 "	.672
		47.0 "	1.116
		46.5 "	1.236
C.	49.3 cm.—50.25 cm.	48.3 "	1.273
		48.8 "	1.138
		50.8 "	.565

CONCLUSION.

It appears from curves (B) and (C) that the velocity of the string at the outer edge of the bowed region is the same as the velocity of the bow. But the curve (A) shows that the forward velocity of the string at a point away from the outer limit of the region is equal to the velocity of the bow. Thus the string in the bowed region, in this case, has smaller velocity than the

Fig. 3.

bow. The most important thing to be noted here is that the note emitted by the string is strong in the fundamental. This is shown by the photographs which are of simple Helmholtzian type of two step zig-zag. It is thus possible to get a steady fundamental when the forward velocity of the string in the bowed region is less than the velocity of the bow.

The curve (A) shows that the "zero point" (*i.e.*, the point which has forward velocity relative to the bow, equal to zero) is away from the outer edge of the bowed region. One would think it possible, by increasing the bowing pressure without increasing the velocity of the bow, to bring the "zero point" to the outer edge of the bowed region. This has been shown to be the case by a series of photographs, as in Fig. 4,

Fig. 4.

of the simultaneous motion of the bow and of a particular point of the string away from the outer edge (2 cm. from it) with different bowing pressures. When the bowing pressure is small while the velocity of the bow is great¹ the "zero point" goes away from the outer edge towards the middle point of the string and the records of the pin and the string become parallel or very nearly so. When, however, the bowing pressure is greater while the velocity is smaller or nearly the same as before the "zero point" comes nearer the outer edge and the angle between the two records appreciably increases.

Thus the "zero point" may lie anywhere within a portion of the string, one of its limits being the outer edge of the bow. The other limit for which the vibration remains two step zig-zag of the first type has not been determined. But the photographs, taken, show that it may be at a distance of about 2 cm., if not more, from the outer edge. It should be noted, further, that the effect due to any increase of bowing pressure can be counterbalanced by a corresponding increase of the velocity of the bow. Thus it will be possible to have the "zero point" away from the outer edge even with a high pressure provided the velocity of the bow is correspondingly high. If then the velocity of the bow is increased keeping the bowing pressure constant or the bowing pressure is decreased keeping the velocity constant, the "zero point" goes away from the outer edge towards the middle point of the string and the

¹ The note emitted is strong in the fundamental.

intensity of the fundamental decreases until the octave becomes most prominent. This can be easily seen in the case of the mechanical violin-player of Dr. Raman.

In the case of two-step vibrations of the first type, the amplitude of oscillation of the string at the outer edge of the bowed region is given by $(1 - a/l)Tv$, where a is the distance of the point from the end and v its forward velocity, l being the length of the string. If the velocity of the bowed point were the same as the velocity of the bow (*i.e.*, v = the velocity of the bow), as was supposed by Helmholtz and others, the amplitude of oscillation of the bowed point, *i.e.*, the intensity of the note emitted, would be independent of the bowing pressure, depending on the velocity of the bow. But it has been shown that the bowing pressure can change the value of v at the outer edge even when the velocity of the bow is constant. Thus the intensity of the note emitted can be varied slightly but appreciably, simply by varying the bowing pressure.

It will appear from the curves which are approximately straight lines that the nearer the bowed region is to the end the steeper is the curve, *i.e.*, the more rapid is the change in the forward velocity per unit length of the string within and near the bowed region. Thus the portion of the string in contact with the bow during vibration will be more and more inclined to a line perpendicular to the direction of bowing. And so a greater component of the frictional force will go to produce longitudinal vibration in the string. This effect is very marked when the bow is applied near the bridge.

Let us see if the results obtained are in agreement with what follows from dynamical considerations. It is obvious that the velocity of any portion of the string within the bowed region cannot be greater than that of the bow; for in that case the frictional force will act in the opposite direction and bring down its velocity to the velocity of the bow. Further it is not possible for every element of the string in the bowed region to have the same velocity as the bow. The "zero point" therefore, cannot lie within the bowed region or between the bow and the nearer end of the string as in that case a portion or the whole of the string in contact with the bow will have velocity greater than the bow which is not possible. So the only portion in which the zero point can lie is between the outer edge and the middle point. And this is exactly what the experiment shows.

THE WOLF NOTE.

The results obtained throw some light on the nature of the "wolf note"¹ produced in bowed stringed instruments. It is evident from the photographs of wolf-note² that the inclinations of the line representing the forward motion of the string changes periodically, the period being the period of the wolf. From this it can be concluded that during the wolf the "zero point" oscillates periodically with the beating, though the pressure and velocity of the bow are constant. And it is only when, by increasing the bowing pressure, the "zero point" is fixed at the outer edge, that the wolf is controlled.

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¹ Dr. C. V. Raman pointed out in various papers (vide "On the Wolf Note in Bowed Stringed Instruments," *Phil. Mag.*, 1916; also Bulletin No. 15 of the Indian Association) that at a particular pitch known as the wolf note pitch, a very peculiar beating note can be produced which however can be controlled by sufficiently large bowing pressure. He also showed that similar beating notes can be obtained at half the wolf note pitch. I have found that this sort of beating note can be obtained *e.g.*, in a violin at a large number of pitches, some of which are as strong as that at the wolf note pitch. They can, however, be controlled by increasing the bowing pressure. A little practice in bowing is necessary as some of them are produced by pressure varying within a small range.

² Bulletin No. 15, Indian Association for the Cultivation of Science.

Fig. 4.