XXXIV. Simultaneous vibration-curves of string and bridge photographically obtained from a monochord

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h/a	1/100.	1/10.	1/5.	1/4.	1/2.	3/4.	1.	2.
β	0.5159	4.059	6.299	7.209	10.38	12.34	13.59	16.15
h/a	3.	4.	5.	6.	7.	8.	9.	10.
β	17.22	17.80	18.16	18.41	18.59	18.73	18.84	18.91

When h is greater than $40a$ we may write

$$L = 19.74(1 - 4a/3\pi h)(a^2/h)N^2; \quad . \quad . \quad (50)$$

and when h is greater than $400a$, we get the well-known formula

$$L = 19.74(a^2/h)N^2.$$

XXXIV. *Simultaneous Vibration-Curves of String and Bridge photographically obtained from a Monochord.* By E. H. BARTON, D.Sc., F.R.S.E., Professor of Experimental Physics, and J. PENZER, Research Scholar, University College, Nottingham*.

[Plates XI. & XII.]

PREVIOUS papers in this series have dealt with (i.) the belly† and string, and (ii.) the air‡ and string; the present communication gives the results experimentally obtained for the bridge and string of the same monochord. The motions of the bridge are recorded vertically and horizontally, the string being excited both by bowing and plucking. Examples of beats are also obtained by using in addition to the vibrations of the string those of a tuning-fork placed upon the instrument. In the later figures curves are shown for the bridge and string when the latter is weighted in the middle so as to make its partial tones inharmonic.

Experimental Arrangements.—The string's motion is obtained and recorded as in the previous papers. The bridge's vertical motion is detected and photographed by the rocking motion of an optical lever, as in the case of the motion of the belly in the first paper. These effects are shown in figs. 1–6 & figs. 14–26 (Plate XI.), in which the string's

* Communicated by the Authors.

† Barton & Garrett, Phil. Mag. July 1905.

‡ Barton & Penzer, Phil. Mag. Dec. 1906.

lantern and passes through the pin-hole S_1 (fig. 1) in a tin-foil screen, falls upon the mirror M_1 of the optical lever, and is thence reflected to the lens L_1 which focusses it upon the photographic plate at R which is on rails in a dark room. The normal to the mirror is $M_1 N$, and $M_1 A$ shows the axis about which it rotates if the bridge moves lengthwise of the string.

In the ordinary use of an optical lever as previously made, the plane of rotation coincides with that of incidence and the reflected beam describes an angle exactly double that described by the lever. Or, if these angles are respectively called δ and μ , then $\delta/\mu=2$.

But in the special arrangement and use of the optical lever here adopted, not only are the planes of rotation and incidence inclined, but also the normal to the mirror is inclined to the axis of rotation of the lever. Hence, as the lever turns, the reflected beam traces out a conical surface instead of a plane. And the angular magnification δ/μ varies according to the circumstances of the case between its limiting values unity and infinity! Thus when the lever turns through the small angle μ about its axis $M_1 A$, let the point N on the mirror's normal rise to N' , and let R in consequence rise to R' . Then since I, N' and R' are in the plane of incidence and reflexion, $I N' R'$ is a straight line. Hence

$$RR'/NN'=RI/NI. \text{ Also } \mu=NN'/AN \text{ and } \delta=RR'/AR.$$

If we now write α for the angle AM_1N between the axis of rotation of the lever and the normal to the mirror, and θ for the angle of incidence $I M_1 N$, it can easily be shown that the angular magnification is given by

$$\delta/\mu = \frac{2 \tan \alpha}{\tan \alpha - \tan \theta}.$$

Thus, if the incident beam is coincident with the axis of rotation, $\theta=-\alpha$ and $\delta/\mu=1$. Again, if the incident beam is along the mirror's normal, $\theta=0$ and $\delta/\mu=2$ as in the ordinary form and use of the optical lever. But if the angle of incidence is nearly equal to α , the reflected beam is almost coincident with the axis of rotation and the *angular* magnification is very great. Thus writing $\theta=\alpha$ we have $\delta/\mu=\infty$!

In dealing with the actual magnification of the arrangement used, it is convenient to first omit the lens L_1 and find as above how R would move to R' by the action of the optical lever simply. Next trace this reflected beam back through the mirror M_1 to the virtual image of the pin-hole S_1

and find the consequent motion of this virtual image. Finally, omit the mirror M_1 but regard the lens L_1 as present, and find the motion of the bright spot on the photographic plate at R as due to the lens L_1 which focusses upon it the virtual image of S_1 in the mirror M_1 . A calculation on this principle gave the linear magnification of the bridge's motion lengthwise of the string to be 108 on the original negative.

By inserting a piece of very thin blown glass under the leg of the optical lever, see P_1 (fig. 2), and noting the consequent movement of the bright spot on a card, the linear magnification was estimated as 93 times. Thus we may say that the magnification near enough for our purpose is of the order 100.

The exact action of the optical lever is best seen from fig. 2, in which it is shown detached from its place at the bridge, where when in use it is secured by indiarubber bands so as to keep its three legs in contact with the hole, slot, and plane shown by H and S on the bracket P Q R and by P_1 on the bridge B. The plane P_1 consisted of a piece of glass cemented on to the head of a pin driven home into the bridge. On the optical lever O L is seen a little tie-piece or strut from the mirror M to the plate L. Before that piece was inserted the mirror yielded a little in the middle of its rotation, and so displaced the spot *horizontally* in the photographic plate. And though this yield was of the order of only two minutes of arc, it produced a horizontal motion of about 2 mm. on the plate and rendered it worthless.

In conjunction with the above special optical lever the optical arrangements for recording the motion of the string, now of 0.88 mm. diameter, are seen in fig. 1. In this M_2 represents a mirror of black glass which diverted part of the beam from the lantern to the tin-foil screen having a vertical slit at S_2 , whence the light passed to the lens L_2 which focussed a bright image of the slit on the string at a point about 5 cm. from its centre. Thence the light fell upon the mirror M_3 , this reflected it to the lens L_3 which focussed it upon the plate at R. The string's motion is accordingly shown on the prints by a black line on a light ground due to its shadow crossing the bright image of the slit. The motion of the string at this point is hereby magnified $1\frac{1}{2}$ on the original plates. So on those and the reductions accompanying this paper, the relative magnification of the bridge's motion lengthwise of the string is $100/1\frac{1}{2} = 67$ nearly.

In all the prints and their reproductions the left side corresponds to the beginning of the time and the string's

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motion is inverted. The bridge's motion vertically in figs. 1-6 and 14-26 is also shown inverted. In figs. 7-13 and 27-47 showing the motion of the bridge horizontally the high positions of the spot denote a yielding of the bridge towards the centre of the string.

Results.—The curves obtained by these experiments are represented in the 47 photographs on Plates XI. and XII., each showing the simultaneous vibrations of string and bridge. These fall naturally into five groups which are taken in order below.

Group I. includes figs. 1-6 in column 1 of Plate XI. These show the vertical movements of the bridge, the string being excited by bowing and plucking at the places shown in the margin of the plate.

Group II. includes figs. 7-13 in column 1 of Plate XI. These show horizontal motions of the bridge parallel to the length of the string, the string being excited by bowing and plucking as noted against each figure. Two examples of beats are represented in figs. 9 and 10. In the former the string had a frequency of 138 per second and was plucked at 10 cm. from the bridge whose motion is shown, while a fork of 128 per second was excited by striking and then held vertically with its stem on the belly of the sound-box at 18 cm. from the bridge. The photographic plate was also shot slower than usual in the hope of showing a couple of maxima or minima of the resultant vibrations. This state of things was not obtained, but as the left end of the print indicates the beginning of the time we see there is evidence of increasing amplitude, thus proving that the bridge could take up vibrations from a fork on the belly although the string was passing over it and vibrating at a different frequency. This plate paved the way for the next, fig. 10, in which beats were obtained by the device of making them 18 per second instead of 10 and shooting the plate still slower than before. In this case the frequency of the string was raised to 146 per second, and the 128 fork was held upright with its stem on the bridge near the point B in fig. 2. The string as before was plucked at 10 cm. from this bridge. The upper half of the print shows clearly two maxima of the resultant vibrations of the bridge, while the lower part shows that the string's vibrations were dying away.

Group III. consists of figs. 14-26 contained in column 2 of Plate XI. Here bowing at a tenth of the string's length is adhered to throughout, the pitches forming the tempered chromatic scale of frequencies 92 to 184 per second. All the figures in this group show the vertical motions of the bridge.

Group IV. consists of figs. 27-39 contained in column 3 of Plate XI. These all show the vibrations of the bridge parallel to the length of the string, which is throughout bowed at 90 cm. from the bridge as in the previous group. Thus columns 2 and 3 of Plate XI. allow comparison of the two motions of the bridge under given conditions of pitch and excitation. They also allow of comparison with the corresponding columns in the previous papers*, where the motions of belly and air were shown.

Group V. comprises figs. 40-47 on Plate XII. Here the string is loaded in the middle by having a wire coiled round it and cemented where necessary to preclude all jarring. In the first column of this plate the photographic plates were shot fast; in the second slow, to obtain more vibrations on a plate and reveal the progressive changes in type due to the inharmonic relation between their partials. In all these figs. the white curves show the bridge's motion lengthwise of the string. The loads used had masses which were respectively 0.002, 0.004, and 0.008 of the mass of the string between the bridges. After fig. 42 the attempt to bow the string was abandoned. A moment's reflection will show its difficulty. When the string carries a load at the middle each partial having a node there is unaffected in pitch, *i. e.* all the evenly-numbered partials. Whereas all the other partials having an anti-node at the middle are flattened by the presence of that load. Hence, when the string is tightened to restore the fundamental tone to its original pitch, all the even partials are sharpened. But the compound vibration excited by the forcing action of the bow must be strictly periodic, and hence by Fourier's theorem all its partials commensurate. Thus when the departure from this state of things is slight the bow can force the partials into tune, but when the departure is great the bow refuses to "bite" and it becomes difficult to coax the string to speak with any tolerable quality of tone.

Accordingly for the figs. 44-47 constituting the second column of Plate XII., plucking only was adopted. And this had the advantage of leaving each partial free to vibrate at its own natural period although inharmonic with the others. The inharmonic character of the partials, of course, causes a slight change in the resultant vibration as their relative phases vary. And this progressive change of type is well shown in these four figures, where the plates were shot slow so as to obtain a number of complete vibrations on each. These curves give a graphic representation of the disturbance

* Phil. Mag. July 1905 and Dec. 1906.

caused by any irregularity in a musical string on a violin or harp, and illustrate the impurity of tone which must follow. The curves show also that these irregularities are all taken up by the bridge, and so no doubt extend to the sound-box and the adjacent air.

Looking now over the results as a whole for the bridge's motion, it is noteworthy that the fundamental tone of the string is also revealed in the vibration of the bridge. Whereas it might have been thought that whether the string were up or down the bridge would be equally deflected inwards towards the string's centre*. But if this were the case the fundamental would be lost by the bridge, its slowest vibration being the octave. This, however, is not the case, as all experience shows and as is confirmed by the curves.

As to the general character of the vibrations of the bridge, they seem to be intermediate in type between those of the belly dealt with in the first paper and those of the air dealt with in the second.

University College, Nottingham,
Dec. 21, 1906.

XXXV. *On the Appreciation of Difference of Phase of Sound-Waves.* By L. T. MORE, *Ph.D.*, *Professor of Physics*, and H. S. FRY, *Ph.D.*, *Instructor in Chemistry*, *The University of Cincinnati*†.

THE experiments described in this paper, in which an attempt has been made to show that we can locate sounds by an appreciation of the difference of phase of the waves coming to the ears, were carried out during the winter of 1902. Certain psychologists, to whom the results were submitted, considered them to be inconclusive, and their publication was postponed until additional work could be done. But this winter Lord Rayleigh, in his Sidgwick lecture‡, described some experiments he had performed which convinced him that we do locate sounds, partially at least, by this means. As his method differs considerably from ours, it seems best to publish these in spite of some incompleteness.

There have been several attempts made to prove that the ear is capable of detecting phase-differences of sound-waves as well as their amplitude and complexity. Apparently the attempts have not had much success, and König is perhaps the only one who maintained that one could distinguish two

* Compare the longitudinal form of Melde's experiment, see Rayleigh's 'Theory of Sound,' 2nd ed. vol. i. p. 81.

† Communicated by the Authors.

‡ See Phil. Mag. [6] xiii. p. 214 (1907).