Physics. — *"On the motion of the bridge of the violin"*. By J. W. GILTAY and Prof. M. DE HAAS. (Communicated by Prof. H. KAMERLINGH ONNES).

(Communicated in the meeting of November 27, 1909).

1. In the following lines an account is given of an experimental research the object of which was to make a contribution to our knowledge of the manner in which the vibrations of the strings are transmitted to the roof of a violin by the bridge.

As far as we know the literature on the physics of bow instruments is very limited and leaves the true nature of the motion of the bridge undecided.

HELMHOLTZ [1]) says: "Der eine Fuss des Steges ruht auf einer relativ festen Unterlage, nämlich auf dem sogenannten Stimmstocke, einem festen Stäbchen, welches zwischen der oberen und unteren Platte des Körpers eingebaut ist. Der andere Fuss des Steges allein ist es, welcher die elastischen Holzplatten und mittels deren Hilfe die innere Luftmasse des Körpers erschüttert."

From this description cannot be inferred whether the bridge vibrates principally in its own plane i. e. at right angles to the longitudinal direction of the strings, or at right angles to its own plane i. e. in the direction of the strings.

VAN SCHAIK [2]) remarks: "By the vibrations of the bowed string a motion of the bridge is set up which consists in an oscillation about a line parallel to the length of the violin: in this manner the movable foot of the bridge communicates vibration to the roof of the violin and thus to the air." His opinion therefore is that the bridge vibrates in its own plane perpendicularly to the direction of the strings.

APIAN-BENNEWITZ [3]) observes: "dass nämlich der rechte Fuss eine viel geringere Bebung als der linke zu machen hat und dass die Thätigkeit des linken Fusses als eine hämmernde zu bezeichnen ist." His view is thus the same as VAN SCHAIK's, as appears further from page 133 of his book.

BARTON [4]) in conjunction with GARRET and afterwards with PENTZER has

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[1]) Tonempfindungen, 3e Ausg. p. 146.

[2]) Dr. J. BOSSCHA, Leerboek der Natuurkunde, III, bewerkt door Dr. W. C. L. VAN SCHAIK, 5th Ed., p. 170.

[3]) Die Geige, der Geigenbau und die Bogenverfertigung. WEIMAR, BERNHARDT FRIEDRICH VOIGT, 1892, p. 125.

[4]) Philosophical Magazine, 6th Series, Vol X, XII and XIII.

investigated the nature of the vibrations of the string, bridge, and roof of a sonometer as also of the air inside the sonometer. He examines both motions of the bridge and finds that for the same point of the bridge the displacement by the horizontal motion, i. e. in the direction of the string, is about 17 times the amplitude of the vertical motion [1]). As the bridge of the sonometer is entirely different in shape from the bridge of the violin and the sonometer is moreover not fitted with a sound bar, the results of the investigation are not immediately applicable to the motion of the bridge of the violin.

SAVART [2]) in his very important memoir on string instruments does not refer to the motion of the bridge.

2. It seemed to us a priori somewhat improbable that as VAN SCHAIK and others suppose a comparatively massive object like the bridge by vibrating as a whole in its own plane about one of its corners should be able to follow completely the intricate motions of the strings and communicate them to the roof of the violin. It seemed to us more probable that, as BARTON found for the sonometer, both motions should be taken into account.

In order to investigate this experimentally we proceeded as follows.

Fig. 1 represents a violin-bridge manufactured by the well known makers CARESSA & FRANÇAIS of Paris. Fig. 2 shows a small

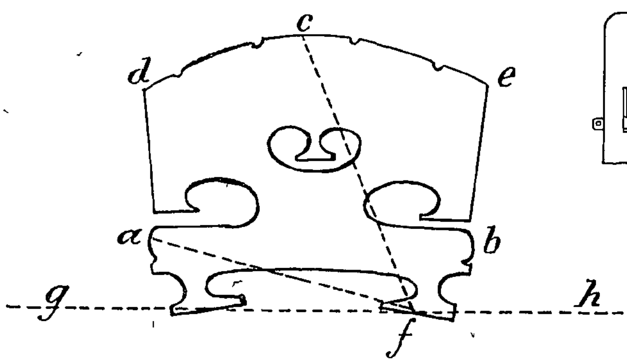

Fig. 1.

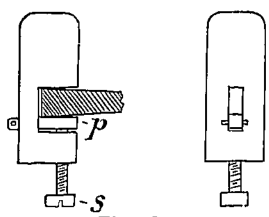

Fig. 2.

metal clamp which can be attached to the bridge at different points. In order not to damage the bridge the screw *s* does not press

[1]) Phil. Mag. Ser. 6, Vol. XIII, p. 451.

[2]) "Mémoire sur la construction des instruments à cordes et à archet." A reprint of this paper is to be found in: "Nouveau Manuel complet du luthier", by MAUGIN and MAIGNE. Paris, librairie encyclopédique de RORET, 1894, p. 333—398.

directly against the bridge but against a moveable piece of steel *p* The weight of the clamp is rather more than 7 grammes.

If the bridge swings in its own plane about its right foot *f*, then when we attach the clamp to the bridge at *a*, the moment of inertia of the bridge about the axis of rotation at *f* perpendicular to the plane of the bridge will be much increased.

On the other hand when we fix the clamp at *b*, the effect on the moment of inertia will be much smaller.

We found however that there was very little difference in the sound of the violin in the two cases. By fixing the clamp at *a* some damping influence was noticeable in the *g* string; at *b* the *e* string was somewhat damped.

In view of the effect of the clamp being about the same in both cases it is difficult to conclude that the bridge swings principally in its own plane about one of its feet. Moreover the influence of the damper was in *both* cases very small.

The following experiment speaks even more clearly.

The distance between the middle of the right foot and the middle of the upper edge of the bridge *fc* is in our case 38 mms. The distance *fa* is 37 mms.

When the clamp is placed at *c* a strongly damped sound is obtained: this is the well known mute-effect, but even stronger in our case than with the ordinary mute which weighs only about 4 grammes as against ours which weighs over 7 grammes. At *a* the effect is as we saw, extremely small.

As *fc* and *fa* are approximately equal, the increase of the moment of inertia of the bridge is about equal in both cases. If the sound were transmitted by the bridge chiefly by its vibrations about an axis at *f*, the damping effect of our clamp should be about equal in both positions.

As this appears not to be the case we cannot but infer from these experiments that the motion of the bridge in its own plane is not of primary importance for the transmission of the vibrations of the strings to the roof of the violin.

We subjoin as an instance some results obtained by two independent observers each playing his own violin.

Violin with strong sound, about 50 years old, maker unknown, model MAGGINI, very large.	Old violin by a pupil of STAINER's, small strongly arched model, fine mellow sound, but not strong in tone, *d* string least fine, *a* string by far the best, *e* also very good.

Metal damper at *a*. (Fig. 1).

Some damping effect, especially on the *g* string. Rather strong nasal sound.	*g* string much less fine than without damper. *d* harder and inferior. *a* inferior. *e* improved. none of the strings damped, respond as promptly as without.

Metal damper at *b*.

Some damping effect, especially on the *e* string. *e* better than usual.	*g* string better than usual. *d* ,, worse ,, ,, *a* ,, ,, ,, ,, *e* ,, ,, ,, ,, *g*, *d* and *a* respond more promptly than otherwise. The *e* string is slightly damped.

Metal damper at *c*.

Damping much stronger than at *a*. Effect the same as with a mute, only less good than with an ordinary mute.	Mute effect on all strings, but much more strongly damped than with the ordinary mute.

It will be seen that the two observers agree entirely as regards the main effect: the damper at *c* gives the ordinary mute effect. At *a* and *b* the effect is absent or at least only very small; again both observers find the effect of placing the clamp at *a* about the same as at *b*.

The small differences in the results of the two observers may be due to individual differences but also to the great difference between the two instruments.

The following observations prove also, that the parallel motion of the bridge has little influence in the transmission of the string motion to the roof of the violin.

The observers and violins were the same as in the previous experiments and the same damper of 7 grammes was used.

Metal damper at *d*. (Fig. 1.)

Mute effect, strongest on the *g* side.	*g* string strongly damped.
	d string less, bad in tone.
	a string still less, bad.
	e ,, ,, ,, ,,

Metal damper at *e*.

Damping, diminishing towards the *g* side. The *g* string has retained its original tone better than the *e* string in the *d* position of the damper.	*e* damped, but much less than the *g* in the *d* position of the damper.
	a less damped.
	d damped, gives the mute-sound more than the *a* string, but is still comparatively strong in tone.
	g less damped than *d*, very ugly.

Both observers thus found, that in the position *d* the damping effect diminished towards *e* and vice versa.

Thus e. g. in the *e* position of the damper the *g* string was but little damped, although in this case assuming the bridge to vibrate chiefly in its own plane, the *g* string would act on a bridge with much increased moment of inertia which would involve strong damping.

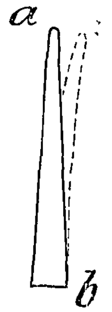

Fig. 3.

We think therefore that we may infer from these experiments that the motion of the bridge does not principally take place in its own plane about one of its feet, but that it vibrates chiefly transversely, as shown diagrammatically in Fig. 3 where *ab* represents the bridge in section. On this assumption the results of all the above experiments are completely explained :

I. A damper placed at *a* has much less damping influence than a damper at *c*, as the moment of inertia about *gh* is much less increased in the former case.

II. The effect is about the same whether the damper is attached at *a* or at *b*. It is clear that the moment of inertia of the bridge, with the clamp attached, about *gh* has about the same value in the two cases.

III. Again the results of the second set of experiments become intelligible when a transverse vibration of the bridge is admitted: we found in that case that the damping effect diminished towards the right when the clamp is fixed at *d* and vice versa. By weighting the bridge at the top corners the vibration is no longer symmetrical; the part which is loaded at the top will vibrate less strongly than the unloaded part.

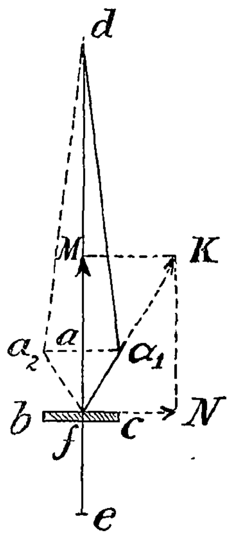

Fig. 4.

3. An additional question with regard to the two motions of the bridge suggested itself in the investigation. In fig. 4 *de* represents the string at rest, *bc* the bridge: when the string is deflected to the right (da_1f), the tension K of the string has a component M at right angles to the plane of the bridge and a component N in the plane of the bridge. When the string has its greatest deviation to the left, the component M has the same direction as before, the component N the opposite. It follows that the bridge completes two vibrations in the direction of the string to one vibration of the string itself, whereas the motion parallel to the bridge has the same period as the string.

The sound of the violin is produced almost exclusively by the vibration of the roof; the string by itself imparts but a very small amount of energy to the air directly. If we suppose that the sound given by the string directly may be neglected in comparison to the much stronger sound which is due to the roof, and that the effect of the parallel motion of the bridge may also be neglected as against the much greater effect of the transverse motion, all the notes of the violin should be an octave higher than the pitch of the string, assuming that the strings deviate on both sides of the position of equilibrium.

The correctness of this conclusion however did not seem to us very probable: presumably if real, this striking fact would have been observed and communicated by previous observers.

We have therefore investigated the question experimentally by putting a steel string on a violin and making it vibrate electromagnetically.

We took a steel guitar string and put it in the position of the *d* string. Close to it a small electromagnet of the ROMERSHAUSEN type was fixed in a stand about vertically above the string, near the place where it is usually bowed. The coil of the electromagnet was in circuit with three accumulators and a KÖNIG electromagnetic tuning fork ($Fa_3 = 682$ v. s.). The fork was placed in a distant room. The tension of the string was regulated until the violin when the string was bowed gave a note slightly lower than the fork. The fork was then started and the note of the string raised by pressing it with the finger until no beats were heard.

The note given out by the violin was now unmistakably Fa_3.

Now if there really were a difference of an octave between the note of the violin (Fa_3) and the note of the string itself, the string ought under the influence of the electromagnet to have given the note Fa_2. This is however impossible: an electromagnet magnetised by a fork Fa_3 can produce in a string the notes Fa_3 Fa_4, Fa_5 etc. but never the note Fa_2. The experiment was thus by itself sufficient to show that the note given by the violin has the same pitch as the note of the string itself, even when the excursions of the string on the two sides of its position of equilibrium are about equal.

Thinking that the octave might perhaps appear, if the parallel motion of the bridge were damped down, we loaded the left foot of the bridge with our metal clamp, but even then the octave could not be heard.

As the question seemed to us of great importance we tried to solve it in a different more direct manner by an experiment in which the sound of the string was heard by itself.

On a heavy zinc-block of 80 by 40 cms and 3 $^1/_2$ cms thick (Fig. 5), two metal bridges are fitted (Fig. 6) at a distance from each other of 32$^1/_2$ cms. An *a*-string 0,7 to 0,75 mm thick was tied

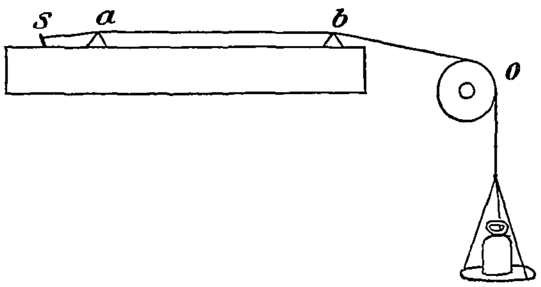

Fig. 5.

to a pin *s*, the other end being attached to a cord going over a pulley and a pan weighted with 6 kilogrammes. When bowed the string sounded a note near Ut_4. The friction of the string on the bridges and of the cord on the pulley enabled us to slightly alter

Fig. 6.

the pitch by turning the wheel of the pulley. In this manner the string was accurately tuned to Ut_4 (1023,9 v.s), so that it produced no beats in a resonator Ut_4.

Next an a string of the same thickness was put on a violin (fig. 7). The distance of a to b was again 32,5 cms. The violin was clamped

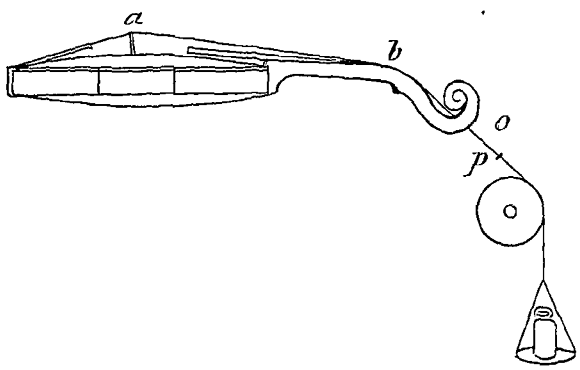

Fig. 7.

on the table with some wooden blocks; in the neck of the violin a hole O was bored, through which the string was made to pass. As the friction of the string on the usual ebony peg would have been too great, a metal peg was substituted which is represented in fig. 8. The string passes over the small metal wheel a. At p a cord was tied to the string which ran over a pulley and had a pan attached to it. The a string was now stretched by placing weights in the pan until the violin on bowing sounded Ut_4 accurately. It was found that a weight of 6 kilograms was required to do this, i. e. the same as with the zinc block.

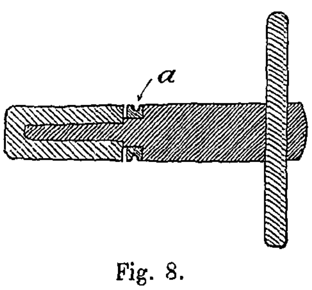

Fig. 8.

That the violin and the string on the zinc block gave the same note, i.e. without a difference of an octave, was confirmed not merely by the ear but also by the aid of resonators: the resonator Ut_4 responded to both notes, the resonator Ut_3 did not. If the note given by the violin had been an octave higher than that of the string on the zinc plate (i. e. Ut_5) the resonator Ut_4 would not have responded to the violin note.

We have also determined the note which the string gave at the above tension by calculation.

For that purpose the string was cut at a and b (fig. 7) whereby its length shrunk to 30 cms. The weight of this piece was found to be 0,15 grams.

By substituting in the formula $t = \sqrt{\frac{pl}{gs}}$ where t is half the period, $p = 0{,}15$ gr, $l = 32{,}5$ cms, $g = 981{,}2$ cms sec^{-2}, $s = 6000$ gr, it follows $t = \frac{1}{1099}$ sec.

According to this calculation the string would have a frequency of $\frac{1099}{2} = 549{,}5$ complete vibrations whereas in reality the frequency was 511,9 (Ut_4).

These numbers agree sufficiently to show with certainty that in both cases the fundamental note of the string was heard. The comparatively small difference can be explained by assuming that the tension of the string was not exactly 6000 grams in consequence of the friction of the string on the bridges and of the cord on the pulleys.

From these experiments it appears that in the mixed sound which the violin produces the fundamental note produced by the parallel motion of the bridge and by the motion imparted to the air directly by the string is still present in sufficient intensity to give the sound the character of the fundamental as far as the pitch is concerned. [1])

It is indeed well known that the fundamental which determines the pitch of a composite note may be of smaller intensity than the overtones of the mixture, as HELMHOLTZ showed to be the case with the piano. [2])

We thus know that the sound given by a violin must be ascribed to three distinct causes:

a. a vibration imparted to the air by the string.

b. a vibration which the roof of the violin acquires from the parallel swing of the bridge.

c. a vibration communicated to the roof by the transverse vibration of the bridge.

The vibration mentioned under *a* will be left out of account as being of little importance.

[1]) Compare RAYLEIGH, "Theory of Sound". second ed. Vol. I p. 208 and BARTON and PENZER, Phil. Mag (6) XIII p. 452.

[2]) Tonempfindungen, p. 134—135.

If a string is bowed the fundamental of which has a period T, the note will be accompanied by harmonics of periods $^1/_2 T$, $^1/_3 T$, $^1/_4 T$ etc. respectively.

The parallel motion of the bridge will cause a periodical change of pressure of its left foot on the roof of the violin. When the bridge moves to the left the pressure increases and vice versa. The change of pressure may be represented by the following series:

$$a_1 \sin 2\pi \frac{t}{T} + a_2 \sin 2\pi \frac{t}{^1/_2 T} + a_3 \sin 2\pi \frac{t}{^1/_3 T} + a_4 \sin 2\pi \frac{t}{^1/_4 T} \dots$$

The transverse motion of the bridge will also cause a change in the pressure between the left foot and the roof. When the bridge is pulled forward the front of the left foot will exert a greater pressure on the roof; when the bridge moves back the pressure diminishes. This change of pressure may be represented by a series of the form

$$b_2 \sin 2\pi \frac{t}{^1/_2 T} + b_4 \sin 2\pi \frac{t}{^1/_4 T} + b_6 \sin 2\pi \frac{t}{^1/_6 T} + b_8 \sin 2\pi \frac{t}{^1/_8 T} \dots$$

As the foot of the bridge has only a small area compared to the large surface of the violin which is set in motion, we may assume that the pressure changes which are due to the parallel and the transverse motions of the bridge respectively, occur *at the same point* of the roof. In order to find the total change of pressure produced by both motions together we must therefore add the two above series. If we assume that the excursion of the roof at the point where the left foot is attached to it is proportional to the change of pressure, the sum of the two series multiplied by a constant will give us the type of motion of the roof at that point.

It is well known that in general a sound becomes mellower according as the partial overtones become weaker and that the intensification of the even overtones especially renders the sound sharper. Many instances of this are to be found in HELMHOLTZ's work already repeatedly quoted (p. 129—133 and p. 151—152). As an illustration of the influence of the overtones on a mixed sound we may also mention the sound of a piano when octaves are played. When an octave is struck on the piano the two notes cannot easily be heard separate, as they can be e. g. with thirds. But only very slight musical training is required to hear in a musical recital that running octaves are played: the sound is then sharper and rougher. The same holds for running octaves on the violin.

When in the above series we diminish the coefficients a_1, a_2, a_3 etc. while leaving the b_2, b_4, b_6 unchanged as far as possible, the fundamental and odd harmonics are weakened more than the even harmonics. In accordance with the above results of HELMHOLTZ the sound will thereby be made sharper. We have proved this in the following manner by experiment:

To the bridge of a violin at the lowest possible point a metal clamp, represented half size in Figs. 9*a* and 9*b*, was attached. On the left side (i. e. on the side of the *g* string) a copper rod 3 mms

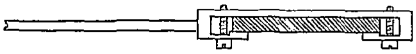

Fig. 9*a*.

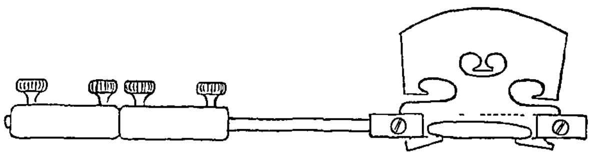

Fig. 9*b*.

thick and 10 cms long was screwed into this clamp. At the end of this rod two ordinary binding screws were fixed, weighing about 18 grammes each.

The moment of inertia of the bridge about the axis through the right foot, perpendicular to the bridge was naturally very much enlarged by these weights. The violin now gave a characteristic nasal sound, especially in the *g* and *d* strings; the timbre resembling most the note of a hautboy. Still notwithstanding the great weakening of the fundamental it continued to impart to the sound the character by which the pitch of a note is distinguished, in other words no change of an octave was perceptible.

When in addition to the clamp shown in Fig. 9*b* the bridge was loaded with two mutes fixed on top of each other and placed on the upper edge of the bridge, the original sound was approximately recovered, as now the transverse as well as the parallel motion of the bridge was damped. Of course the response of the violin at this load was difficult. The two mutes were an ordinary ebony mute with a metal mute, as often used, placed on top.

When a_1, a_2 etc. and b_2, b_4 etc. are all diminished in the same proportion the form of the curve of motion will not change, only the amplitude diminishes: the intensity is weakened, but the timbre remains the same.

If we could diminish the b's and leave the a's unchanged, the sound would become mellower, as in that case only the even upper partials would become weaker, including the first overtone which has the greatest intensity of all.

A mute placed on the bridge damps both motions. But from the fact that it renders the sound mellower we think we may infer that the *b*'s are reduced by it by a higher fraction than the *a*'s. This would mean that the transverse motion of the bridge is damped to a higher degree by putting on the mute than the parallel motion.

5. We have also tried to show experimentally that the bridge in its parallel motion turns principally about its right foot.

For this purpose we screwed two metal rings into the clamp of fig. 9, which were placed in a horizontal position. The violin was fitted with a steel string, as before moved electromagnetically. While the string was moving a small leaden ball was placed alternately in the two rings; the two balls weighed 34 grms each. They were attached to a thin cord; as nearly as possible at the same moment that one ball was lifted out, the second ball was carefully placed in the other ring. We expected that the sound of the violin would be perceptibly weakened as the ball on the right was removed and the left ball simultaneously put in. But we did not succeed in arriving at a trustworthy result in this manner; in the first place a rattling noise was sometimes apparent while the balls were being exchanged and in the second place the tone of the steel string was not always of the same intensity.

6. The conclusion therefore to be derived from our experiments is that the bridge of a violin performs a parallel as well as a transverse motion and that the timbre of the tone, given by the violin, is modified greatly when the intensity of one of the motions is altered while leaving the other motion unchanged as nearly as possible.

Herewith we have at the same time given the physical explanation of the action of the mute and also of the influence which the use of too thick or too thin a bridge has on the sound of a violin.

The action of the mute is commonly described by calling it "damping" or "deadening" [1]). But if the mute caused nothing but a general damping or reducing of the bridge motion, the mute would only weaken the sound, and the same effect would be obtained by bowing softly on a violin without as by bowing hard on a violin with a mute. That however is by no means the case as every one knows.

Delft, November 1909.

[1]) Barton. "Textbook on sound", p. 419: "The mute is a small apparatus of wood or metal which fits on the bridge, and thus deadens the sound considerably".