The Tampura Bridge as a Precursive Wave Generator

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Summary

The tampura bridge generates on a string a quasi-periodic precursive wave, responsible for a strong narrow formant. It arises shortly after the attack, with a slowly decaying frequency. Due to the wave dispersion, at every cycle, the front part of a corner precursor is not trapped between the string-bridge contact and the "juari" thread; these similar "cuts" are "pasted" one after the other, to form the quasi-periodic precursor. This mechanism can be imitated without any tampura. The frequency decay is controlled by the dispersion and by the dampings, including that of the string on the bridge.

Der Tampura-Steg als Generator für Vorläufer-Wellen

Zusammenfassung

Der Tampura-Steg erzeugt auf einer Saite eine quasiperiodische Vorwelle, die für einen starken, engen Formanten verantwortlich ist. Sie tritt kurz nach Anreißen der Saite mit langsam abnehmender Frequenz auf. Aufgrund der Dispersion der Wellen entgeht der Anfang eines Vorläufers in jedem Zyklus dem Einfangen zwischen dem „Jurai"-Draht und dem Kontaktpunkt Saite–Steg. Die ähnlichen „Ausschnitte" werden untereinander verbunden und bilden den quasi-periodischen Vorläufer. Der beschriebene Mechanismus kann auch ohne Tampura erzeugt werden. Die Frequenzabnahme wird durch die Dispersion und die Dämpfung bewirkt, einschließlich der Dämpfung zwischen Saite und Steg.

Rôle du chevalet de tampoura comme générateur d'une onde précursive

Sommaire

Le chevalet de tampoura génère dans la corde une onde précursive quasi-périodique, responsable d'un formant intense et étroit. Elle apparaît peu après l'attaque, sa fréquence décroit lentement. A cause de la dispersion des ondes, à chaque cycle, la partie frontale précursive d'un point anguleux échappe au piège formé entre le fil «juari» et le point de contact corde/chevalet; ces «morceaux» similaires sont «collés» l'un derrière l'autre, pour constituer le précurseur quasi-périodique. On peut imiter ce mécanisme en l'absence de tampoura. La décroissance de fréquence est contrôlée par la dispersion et les amortissements, y compris celui de la corde sur le chevalet.

1. Introduction

The strange sound of the tampura, arising only when the "juari" thread is correctly placed, is surprising and fascinating. The richness of high overtones moves continuously, and our sensation of time tends to change. The listener does not perceive the attacks, and it seems that the instrument is bowed rather than plucked. The physicist would like to understand how this works!

The four strings are always tuned on the same four notes and played according to a unique rhythm. They rest on a wide, curved bridge (Fig. 1 a). Before playing, the musician must adjust carefully the position of the thread called the "juari" thread which is placed between each string and the bridge. As long as the position is not correct, the sound remains poor and dull. The correct place is such that the string lightly touches the bridge when resting on the thread (Fig. 1 b). Therefore the string boundary is the thread when the string is up, and the bridge when it is down. These two places are the same distance apart (about 5 mm; string length about 1 m) however small the amplitude may be. This is specifically what is achieved by the "juari" threads. Somehow, we have two boundaries, at P (thread) and M (bridge contact) instead of the usual one (Fig. 1 c).

Raman suggested earlier [1] that the cause of the peculiar behaviour of the tampura lies in the string movement resulting from the nature of the contact between the string and the bridge of the instrument. He made beautiful photographs of this contact [2], and showed that the string actually leaves the bridge and returns to it, most probably once during a cycle of vibration. He stated that this would account for a periodic change in the length of the string, with the production of an unusual number of overtones.

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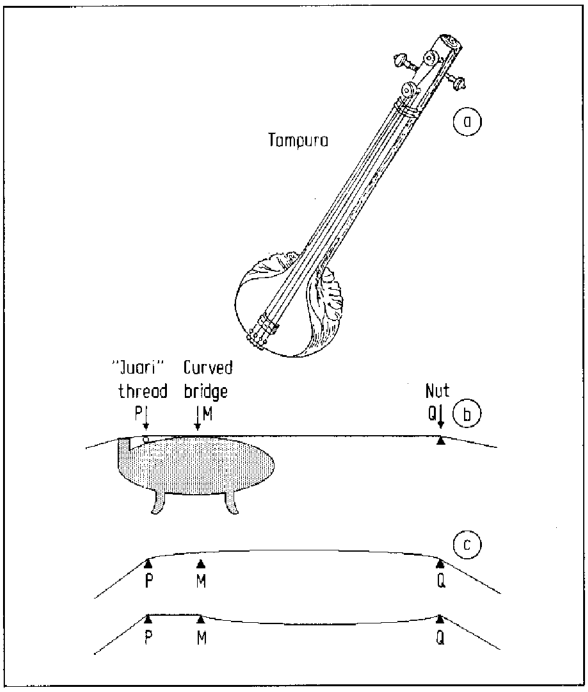

Fig. 1. Presenting the tampura: a) drawing of the tampura instrument, [2]; b) the position of the "juari" thread is P, the curved bridge is M and the nut is Q (not to scale, free style); c) the mechanism of the equivalent two point bridge.

An acoustical study by means of a sonagraph has been made by Leipp [3], who has shown that the striking character of the sound is due to the presence of a strong and narrow formant, the frequency of which slides down during the sound; the attacks are particularly quiet. Anyone who has made a sonagram of a tampura sound will agree with these statements. The anharmonicity introduced by the bridge is not that striking, and of course it does not appear on the sonagram.

More recent publications have examined the tonal quality and the harmonic structure of the tampura [4, 5]. Yet it remains a problem how the nature of the contact between the string and the bridge may generate such a string motion that a strong sliding formant is created, and how quiet attacks can give rise to rich sounds on a plucked string.

2. Experiments

2.1. Experimental arrangement

For musical use, the string is softly plucked with a finger-pad. A useful way for physicists is to pluck it at a point with a plectrum.

The transverse force exerted by the string at the nut of the tampura was measured by means of a small plate of steel, with a strain gauge glued to each side. The plate lies between one of the strings and the nut. Detection was made through a Wheatstone bridge.

As will be detailed below, we have simulated the behaviour of the tampura on our string measuring frame [6]. At first, a tampura bridge was solely mounted on the measuring frame on its own. Then it was successfully replaced by an elementary two point bridge, similar to that of Fig. 1 c.

In all cases, the force signal was visualized on an oscilloscope, and digitized through an A/D convertor. With a 48 μs sampling time, a 2 s signal can be stored in the microcomputer. Temporal modifications of the wave form are studied, and time frequency analysis is performed by means of Spectral Differential Analysis, a powerful signal analysis method [7].

2.2. Preliminary experimental results

Following on the initial idea of Raman, we have studied the string movement using our detectors.

The comparison between the force signals obtained on the complete tampura and those using the measuring frame with a tampura bridge proved that the instrument does not in fact change the motion of the string. As Raman thought, its peculiar features are essentially due to the bridge. Furthermore, very similar results were obtained on our two point simple bridge. This proves that the curved bridge with the "juari" thread is essentially nothing but a two point bridge.

2.3. Existence of a precursor, qualitative results

Just looking at the force signal while listening to it made it clear which part of the wave form was responsible for the formant. For the six successive shapes of Fig. 2, the tampura was initially plucked with a plectrum. The wave part labelled "v" carries energy at a progressively decreasing frequency. The frequency drifts similarly to that of the formant. Subjectively, the ear listening to the formant agrees with the eye looking at "v".

Comparing Fig. 2 with the wave shape usually obtained on plectrum plucked strings with ordinary boundaries [8], we identify the force discontinuity following "v" as the effect of a propagating corner on the string, and "v" itself as a "precursor" of this corner. A flexural wave originated by the high frequencies of the corner propagates ahead of it, because of dispersion (phase speed higher for higher frequencies). This tampura precursor could not have been identified by looking at the sound signal instead of the force signal.

Let us recall the features of a precursor on the usual strings. For a string plucked at a point, two corners propagate. Each corner gives rise to a precursor (high

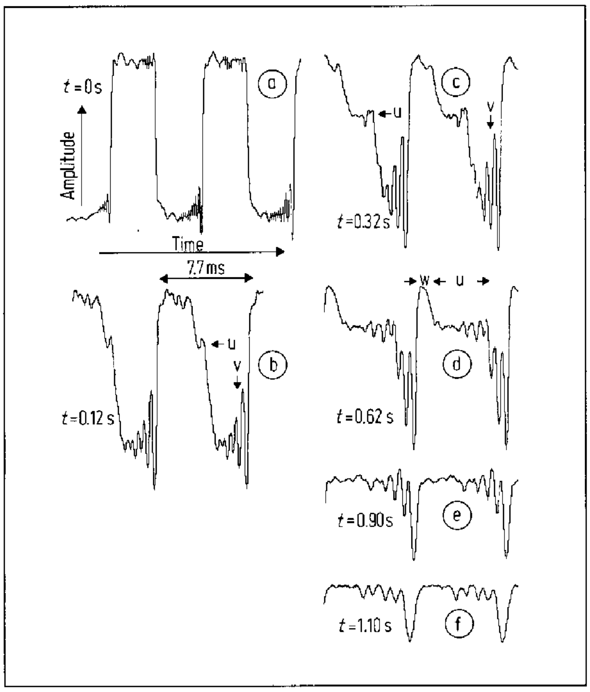

Fig. 2. Six successive shapes showing the force waveform. The tampura was initially plucked with a sharp plectrum. The precursor is labelled "v", the "zero" force step "u", and the remaining positive force "w".

frequencies ahead), which covers a large frequency range (dispersion). These frequencies slowly decay, due to damping and to dispersion (see calculation of the wave form in [8], p. 120, and Fig. 13a, b, c, p. 121). A precursor results from nonlinear effects in a stiff string, it is a pseudoperiodic flexural wave (overtones), and thus has a formant effect. A wide formant is originated by a precursor with a large frequency range.

Let us compare the features of the tampura precursor with the usual precursor previously described more completely. Both have a decreasing frequency (due to damping and to dispersion). Both precursors slowly change over one period of the string (pseudoperiodic flexural waves), and thus have a formant effect (they carry energy at the frequencies of several overtones). However there are two differences. First, for the tampura plucked at a point, only one of the two initial corners originates a precursor, the second one decays and vanishes. Second, the tampura precursor has a fairly well-defined frequency, and thus gives rise to a surprisingly narrow formant.

If the tampura is played with a soft finger-pad attack, the wave form is poor at the beginning (Fig. 3a), but after a while the precursor arises (Fig. 3c), and the wave form (Fig. 3e) becomes quite similar to that of the plucked tampura (Fig. 2d). The attack is soft, but the sound becomes rich as soon as the precursor appears.

All these results were obtained on a tampura. They are identically obtained if all of the tampura except its bridge is removed and replaced by a measuring frame; and, furthermore, if the bridge itself is turned into an elementary two point bridge. The wave forms in Fig. 4 and in Fig. 5 exhibit a close similarity with those of the actual tampura, despite the fact that nothing of the original instrument is left; nothing, that is, but the "essence" of the tampua: two different bridge boundaries depending on whether the string is up or down, however small the amplitude is.

A sonagram of the force signal obtained on our measuring frame, with our two point bridge, is shown

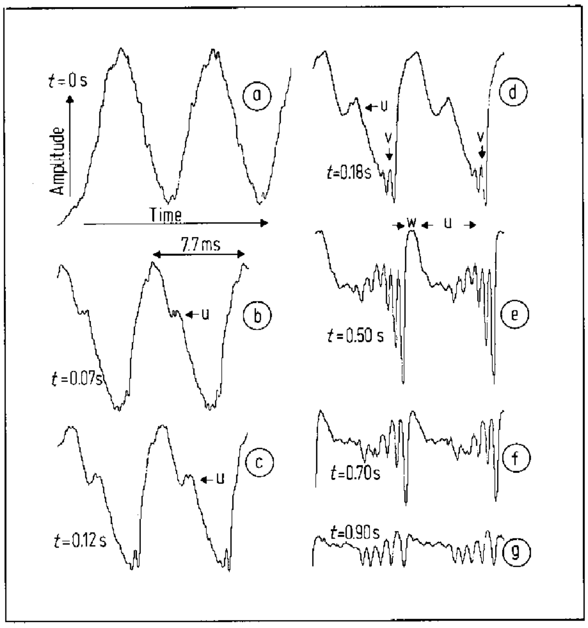

Fig. 3. As in Fig. 2, for a soft finger-pad attack.

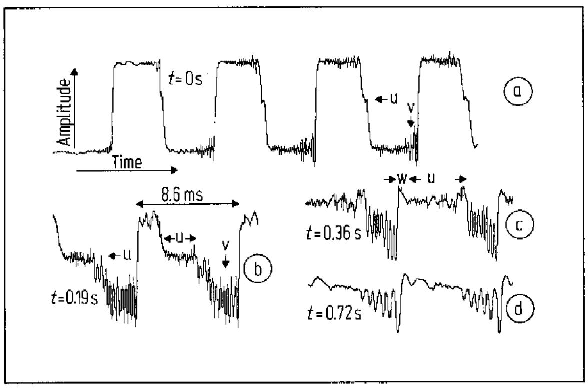

Fig. 4. As in Fig. 2, but for the elementary two point bridge (PM = 21 mm), on the measuring frame (string length is about 1 m).

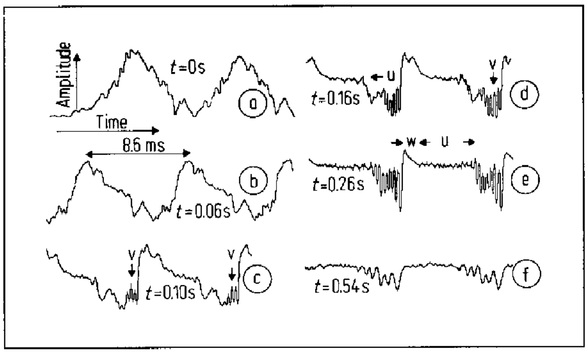

Fig. 5. As in Fig. 4, for a soft finger-pad attack.

in Fig. 6. The attack is soft, the string was plucked near the middle by a finger. Only odd overtones are present at the beginning (the wave form was similar to Fig. 3a). Even overtones soon arise (as in Fig. 3 b, the wave form becomes asymmetric). After some time, the precursor appears, with a constant frequency at the beginning, followed by a decrease. It is noticeable that the precursor has some overtones: the overtones 2 and 3 of the precursor create a formant effect in Fig. 6, labelled "c" and "d". The material of which the bridge is built changes this number. With our two point bridge, a smoothed plastic edge at M gave fewer overtones in the formant than a steel one. In the same way, we have found less numerous overtones with a wooden tampura bridge than with a harder one made out of bone.

2.4. Some quantitative results for the tampura precursor frequency

2.4.1. Experiments

We determined, as mentioned above, the instantaneous frequency of the precursor. We compared its value and time dependency in different situations, in order to see which of the experimental parameters affect the formant. This analytic approach was carried out on our measuring frame, with our two point bridge. The distance between these two points [1], the plucking point, the initial amplitude (playing "forte" or "piano"), and the material of the bridge were varied. Cases where the string is initially plucked with a plectrum (precursor immediately present) or with the finger-pad (precursor arising after a while) were also compared.

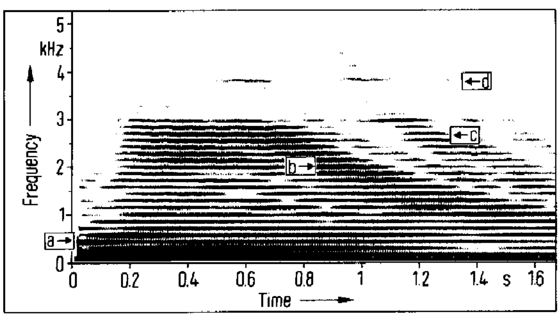

Fig. 6. Force sonogram for a two point bridge (PM = 14 mm) and a soft finger-pad attack. "a": only odd overtones are present at the beginning, but even overtones soon arise. "b": The fundamental frequency of the formant decays, after a flat part (cf. Fig. 8 a, regimes R_2 and R_3). "c" and "d": The second and the third overtones of the precursor have a formant effect.

2.4.2. Results

The distance between the two points of our bridge was the main parameter which affected the precursor (Fig. 7): the shorter this distance, the slower was the

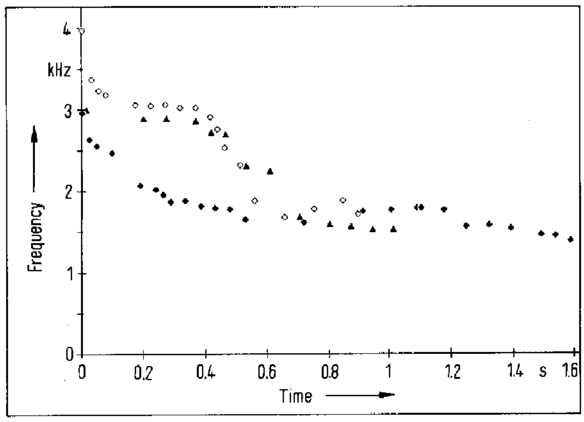

Fig. 7. Precursor frequency decay for a two point bridge, with three different PM distances. (◇) 21 mm, (▲) 14 mm, (◆) 7 mm.

decay time of the precursor frequency. With an actual tampura bridge, this distance can be decreased with a thinner "juari" thread placed nearer to point M. The time evolution also depended on the plucking position.

The precursor frequency did not decay regularly (Fig. 8 a). After a fast initial decrease R_1, a flat part R_2 was reached, followed by another decrease R_3, and finally a flat part R_4.

For a given distance and the same plucking point, the time evolution was not changed when the initial amplitude was lowered (Fig. 8 a). The precursor frequency was not affected if the contact was smoothed by using plastic instead of steel (Fig. 8 a) (but the wave

[1] Perceptually, the anharmonicity introduced by the bridge does not obstruct the feeling of the tone; thus, we do not comment about the induced change of vibrating length.

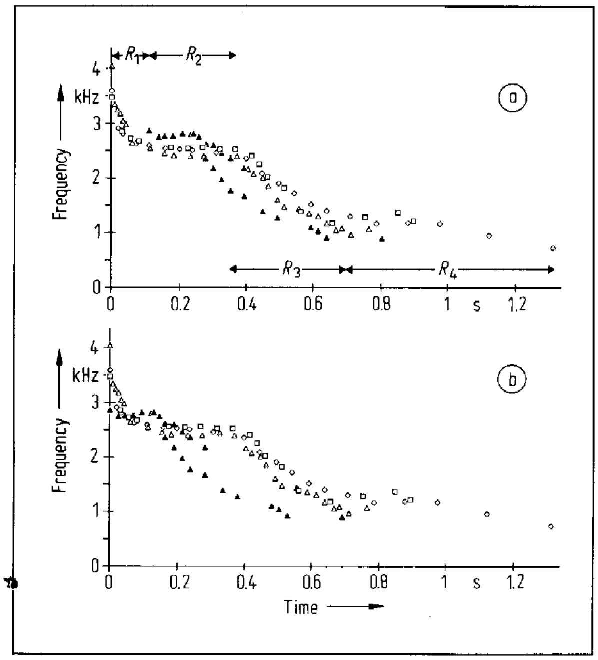

Fig. 8. Precursor frequency decay for a two point bridge (PM = 21 mm), in four different situations (same plucking point):

- plectrum plucked string, high amplitude ("forte"), two steel edges P and M,
- plectrum plucked string, low amplitude ("piano"),
- same as the first one, but M smoothed (plastic instead of steel),
- same as the first one, but soft finger-pad attack. Frequency value of two different parts of the precursor.

a) The four different regimes: first decay R_1, first flat part R_2, second decay R_3, second flat part R_4. With the soft attack, the precursor arises after a while, R_1 section is missing, but R_2, R_3, R_4 remain unchanged.
b) Same as Fig. 8 a, but with the time origin for the soft attack incorrectly taken to be when the precursor appears. The damping of the string affects the whole process, and exists during section R_1 even if there is no precursor present. (□) with plectrum forte (◇) with plectrum piano (△) with plectrum forte on smoothed bridge; (▲) with finger pad forte.

shape was modified, so that the number of overtones of the precursor decreased).

In Fig. 8b, the time origin for the finger-pad plucked string was incorrectly taken to be when the precursor appears, instead of when the string was plucked. The precursor frequency would not follow the usual regimes. In fact, the damping of the string affects the whole process, and exists during R_1 (Fig. 8 a) even if there is no precursor present. The time scale is physically related to the damping. When the precursor is present, its frequency and time evolution (Fig. 8a, R_2, R_3, R_4) do not depend of the nature of the attack.

3. The flexible, dispersive string model; explanation of the experimental results

We have described how the tampura precursor behaves, it remains to understand why it does so. For this we shall find some help in the work we have done on harpsichord strings. Although the understanding of the precursor would necessitate a complete theoretical treatment of a stiff string with non-linear behaviour, which has not yet been developed; a convenient starting point is a flexible string model (geometrical stiffness neglected), in which the dispersive effect (flexible dispersive string) is taken into account [9].

3.1. The flexible, non-dispersive string model, and the experimental facts it explains

Let us consider as a starting point, a flexible non-dispersive string, resting on a two point bridge. Damping due to air viscosity, metal viscosity, dislocation movements and thermal irreversibilities, [6], are neglected. The damping of the string against the bridge itself (stiff bridge), will be explained immediately below. The string is initially plucked by a plectrum (point contact). The shape of the string as a function of time is not difficult to construct geometrically (with a ruler and a pair of compasses), assuming a constant velocity for straight parts of the string (no applied forces), and a constant phase speed along the string. At a corner, a force is applied, a velocity jump occurs in the string, which propagates at the phase velocity. When a corner reaches a fixed boundary, reflection occurs, the phase velocity reverses, whereas the velocity of the string beyond the corner remains unchanged. The result is given in Fig. 9 at 13 different times; characteristic points are labelled in Fig. 9a. Detailed comments are now necessary to understand the model, we apologize for boring the reader, and ask him to be patient.

– Fig. 9 b, the corner "a" runs along AP, the corner "e" runs along AQ; the kinetic energy between "a" and "e" increases (the interval grows between "a" and "e"), whereas the potential energy decreases (the string's geometrical length shortens).

– Fig. 9 c, the corner "a" is trapped between the points P and M; the trapped part of the string will oscillate at a high frequency, let us assume that it will soon decay, even on a stiff bridge, sooner on a "juari" thread. This accounts for the damping of the string on the bridge. A new corner "a_1" is generated at the point M.

– Fig. 9 d, "a_1" and "e" are about to cross at X.

– Fig. 9 e, "e" has just passed through M, it has been partially reflected in "r_1", which runs along MB_1, and partially transmitted in "e_1".

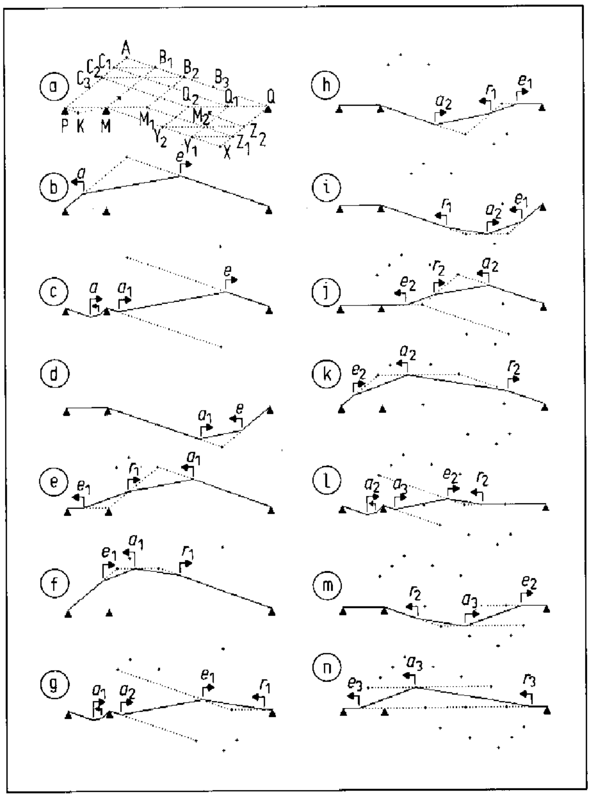

Fig. 9. Theoretical shape of a flexible non-dispersive string, resting on a two point bridge. a) Characteristic points of the geometrical construction are labelled. b) to n) string shape at 13 successive times, detailed explanations in the text.

– Fig. 9f, "a_1" leaves the two segment initial envelope, runs along the segment B_1C_1. It has met "r_1" at B_1, and will meet "e_1" at C_1.

– Fig. 9g, "a_1" is trapped, "a_2" created; "e_1" leaves the initial envelope, runs along C_1Q_1, and is to meet "r_1" at Q_1.

– Fig. 9h, "r_1" is going to meet "a_2" at Y_2, and will run along Y_2M.

– Fig. 9i, "a_2" runs along Y_2Z_2; "r_1" will be totally reflected at M: we shall then label it "r_2", which will describe MM_1.

– Fig. 9j, "e_1" has run along Z_1M_1, it has met "r_2" at M_1. It is convenient to change "e_1" to "e_2" at this point, in order to determine simple recurrence rules.

– Fig. 9k, "a_2" describes B_2C_2.

– Fig. 9l, "a_2" is trapped, "a_3" is created; "e_2" runs along C_2Q_2, "r_2" runs along QQ_2, they will meet at Q_2.

– Fig. 9m, "a_3" describes Y_2Z_2.

– Fig. 9n, "a_3" describes B_3C_3.

The recurrence rules follow straightforwardly, from the polygon $MB_1C_1Q_1Y_1Z_1M_1B_2C_2Q_2Y_2Z_2M_2\ldots$. Each time the string goes on M from upwards to downwards (Fig. 9c, 9g and 9h), it loses the same kinetic and potential energy. The motion stops completely after n periods where n is of the order of $n \cong PQ/PM$ (for clarity, the figures presenting the model are drawn with a very large PM distance and large angles, so that the motion stops rapidly). This explains why the time scale depends mainly on the distance between the points of the two point bridge.

The force exerted by the string on the measurement frame at point Q can also be constructed geometrically. The result, valid for small amplitudes (small angle approximation), is shown in Fig. 10, where the time positions of the 13 string shapes are labelled. Each change in the force corresponding to the passing of point Q by one of the corners, is also labelled in the figure. After the passing of "r_j" ($j = 1, 2, \ldots, n$), the force is just zero; this is the "image effect" of the resting part of the string which has been introduced, at the left of M, when the string moved upwards (Fig. 9e and j). Let us introduce $\alpha \cong AP/AQ$ (plucking ratio) and c = phase speed of the flexural waves. The passings of the corners "e_j", "a_j", "r_j" ($j < n$) are periodic, respectively with periods T, $T-\tau$, $T-2\theta$, where: $T \cong 2\,PQ/c$, $\tau \cong KM/c$, $\theta \cong PM/c$. After some calculation, we find: $\tau \cong 2\alpha\theta/(1+\alpha)$. Thus, τ is smaller or greater than θ according to whether the string is plucked nearer the bridge or nearer the nut. In the middle $\tau = \theta$. This accounts for the effect of the plucking position. These three periods act differently on the whole process and have different physical origins. The corner "a_j" is periodically created and destroyed at two points M and K, whereas "e_j" and "r_j" remain all the time. This difference has a consequence on the tone perception, which will be explained below (next model). The period of time during which the force at Q is oriented downwards (initially $\cong PA/c$), decreases by τ at each period; τ is the duration corresponding to the moving portion KM of the trapped part of the

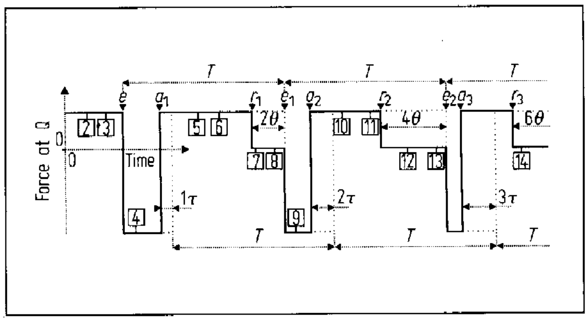

Fig. 10. Force calculated at Q, from Fig. 8 (small angle approximation). The time position of the 13 string shapes are labelled, the passings of the corners also. The three periods T, $t-\tau$, $T-2\theta$ are shown.

string when it goes downwards. The zero force duration grows by 2θ at each period; θ is an additional duration corresponding to the resting part PM of the string, which comes in when the string goes upwards. The time interval, when the force is up, decreases by $2\theta - \tau$ at each period.

When the attack is exactly in the middle, the force signal is initially symmetrical (even overtones rejected). Asymmetry appears and increases because the duration τ always subtracts from the negative section of the force wave-form, and because the duration 2θ always adds a zero force interval at the end of the positive section. The force signal becomes more and more asymmetrical, so that even overtones appear more and more.

This effect has been illustrated in Fig. 6, labelled "a". The zero force part, increasing every period, can be seen clearly in Fig. 4a, labelled "u", and at the three similar places; "u" is perfectly flat in Fig. 4b and Fig. 5e. It is also present with the actual tampura, for instance in Fig. 2b, Fig. 2c, Fig. 2d, and in Fig. 3b, 3c, 3d, 3e, labelled "u". However, in Fig. 2c, Fig. 3c and Fig. 3d, "u" is not exactly flat; this is because the part of the string at rest fits the curvature of the bridge exactly, whereas it is straight for the two point bridge.

3.2. The flexible, dispersive string model, and the experimental facts that it explains

Let us now take into account the dispersion effect. Nothing is changed as far as low frequencies are concerned, and it has been established in [8] that the only change is to create a precursor moving ahead of each travelling corner.

The key of the tampura mystery is given by Fig. 9c, Fig. 9g and Fig. 9l: the trapped corner "a_j" ($j < n$) has developed its own precursor during the last elapsed period. The front part of this precursor has not been trapped. Coming after this front part, a new corner "a_{j+1}" is created, which will develop during the next period a new precursor. The front part of it will not be trapped and will just be added and follows the previous one. The large tampura precursor, responsible for the acoustical formant, is thus built with similar parts of precursors of the "a_j" corners. We understand now why the formant is so intense. Each part of precursor contains high frequencies only, because it is a front part (dispersion effect), so that its frequencies peak about a mean value. The similar parts peak at a similar value, so that the big tampura precursor peaks sharply at a mean value. We understand now why the formant is so narrow.

Its frequency decreases with time as it usually does for precursors, under the combined effects of dispersion and damping [8]. When the distance between the two points of the tampura bridge is changed, the damping varies, and so does the frequency evolution. Furthermore, if this distance is made larger, each non-trapped part of precursor will be further ahead of the corresponding corner. Consequently it will have a higher frequency due to dispersion: the formant will start at a higher frequency. This explains why, in Fig. 7, the formant starts at 4 kHz for 21 mm, and at 3 kHz for 14 mm. When a part of the precursor is trapped, a corner is generated (Fig. 3d, force jump after "v"), although the smooth curvature of the bridge would at first sight seem to make this impossible. One must not forget however that, when this happens, the part of the string coming into contact with the bridge is not straight (oscillations of the precursor).

We also understand now why the "e" corner, on the contrary, gives no formant. We have seen in Fig. 9e that "e" is partially reflected and partially transmitted, thus its precursor splits into two parts. After one period, we have seen in Fig. 9i that "r_2" is totally reflected; but this is not true for its precursor, which is partially reflected and partially transmitted, and thus splits again into two parts. This destructive mechanism is as efficient as the constructive one described above.

Among the three periods T, $T-\tau$, $T-2\theta$ mentioned above, there is only one, $T-\tau$, which is related to the passage of the precursor, and thus has a much greater importance for the ear and tone perception. This explains why, in spite the inharmonicity introduced by the bridge, the tone perception is unambiguous and well defined.

3.3. The damping of the string on the bridge

Our experimental study has shown that the formant frequency decrease follows four different regimes (Fig. 8a, R_i, $1 \leq i \leq 4$). Each regime corresponds to a characteristic wave shape. In other words, the damping of the string on the bridge depends on the oscillating shape of the string. During R_1, the precursor grows when the force is negative (Fig. 4a); according to our model, a constant energy is lost each time the string rests on M, and the string should stop completely when this constant energy cannot be lost any more. In reality, the precursor allows for some complications; the string does not stop completely, but the damping on the bridge drops suddenly at the end of R_1, so that the formant frequency no longer decreases. During R_2 the precursor spreads inside the zero force interval (labelled "u", Fig. 4b); this low damping regime can exist as long as a positive force (labelled "w", Fig. 4c) remains; oscillation should stop if "w" disappeared. When "w" becomes very short, higher damping on the bridge begins, and thus during R_3 a frequency decrease is observed again. During R_4 the amplitude is so small that the string keeps contact with the bridge, and the damping on the bridge vanishes.

When the distance between P and M is short, the damping on the bridge is small, and the other dampings are no longer negligible; the four regimes become less marked: this explains why they are less evident in Fig. 7 for 7 mm than for 21 mm. To produce music, a regular frequency decrease seems to be suitable; on the actual tampura, a short PM distance (5 mm) is used, and the curved bridge seems to induce a more regular decrease than our experimental two point bridge.

4. Comments and conclusion

We have shown that the tampura bridge is a precursive wave generator: as a result of dispersion, the front of a corner precursor is never trapped between P and M, and these similar "cuts" are added one behind the other. Our study was concerned with the force exerted by the string. This force is of course related to the sound of the tampura. The soundboard is very rigid, so that very high frequencies (up to 16 kHz) can be radiated efficiently. Such high frequencies occur if the overtones of the precursor are present: if a harder material is used for the bridge, the overtones of the formant will be more numerous.

A paradox arises when the tampura is compared without the "juari" thread and with it. As far as the force exerted by the string is concerned, the wave energy is higher without the thread than with it (no extra damping on the bridge); but it sounds softer only because of the strong non-linearity of the ear, being less sensitive to the low frequencies of the force signal than to the formant frequencies induced when the thread acts. As far as the sound of the tampura itself is concerned, it is much louder when the thread is used, because of the rigidity of the soundboard which makes the high frequencies more active.

The paradox of the attack is solved: the missing even overtones arise because of the curved bridge; the "juari" thread acts as a two point bridge, which generates the precursor even at low amplitudes.[2] The formant is fascinating because its fundamental frequency lies within the range where the ear is most sensitive, and because it changes with time. This downward slide is carefully adjusted by clever musicians; for instance the formant frequency may go on without any jump [10] when the note changes to the octave below. Our feeling of time is modifed ...!

[2] The sitar also has a curved bridge, but no "juari" thread; the formant raises at high amplitudes only [3]. A remarkable mathematical analysis of the ideal vibrating string with a curved bridge has been done by Burridge et al. [11].

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