THE TOSCA ALEMBA – RINGING THE CHANGES

Moya Henderson* and **Neville Fletcher****
*** 10 Corniche Road, Church Point NSW 2105**
**** CSIRO Australia,** and also **RSPhysSE, Australian National University, Canberra 0200**

Abstract: The *Tosca Alemba* is a new tuned percussion instrument with steel rods bent into pentangular shape as vibrating elements. The vibrations of these pentangles are communicated to a carefully designed soundboard to enhance radiation of their lower modes. The history of the development of the instrument from an earlier *Alemba* using triangular vibrating elements is traced, and the design of the pentangles considered in detail. The shape of these elements is such as to allow the tuning of five mode frequencies so as to produce closely harmonic frequency relationships, including a minor third, and a consequent musically attractive bell-like sound.

1. INTRODUCTION

Many orchestral scores call for the use of percussion instruments for dramatic effect. The timpani are the most commonly used percussion instruments, but cymbals and triangles are also used occasionally. Some compositions, however, make major use of percussion – for example, in the finale to Tchaikovsky's *1812 Overture*, where we find not only church bells but also cannon!

While it is possible, with modern recording and mixing techniques, to use actual church bells and cannon to produce exciting recorded performances of such works, this is much less satisfactory from both artistic and acoustic points of view in live performances. Leaving aside cannon, which could presumably be simulated using real explosives, there is a continuing problem with the production of bell sounds in orchestral performances. This applies not only to the massive sounds required by the *1812 Overture* but also to the much more subdued and carefully scored bells in operas such as Puccini's *Tosca* and Wagner's *Parsifal.* In each of these operas the bells are required to play particular notes, rather than simply making a joyful noise.

The solution usually adopted in orchestras is to make use of sets of tubular bells. These are hollow metal tubes about 20 mm in diameter and up to 1 m long, suspended freely and struck at a carefully selected point near one end. The sound is certainly "bell-like", but not a close approximation to the sound of a church bell. The basic problem is the lack of any low-pitched fundamental to the sound, so that it has clarity but not weight.

With this problem in mind, we have designed and built a new sort of bell-like percussion instrument specifically to produce bell sounds such as are called for in *Tosca* and *Parsifal.* For the present the instrument is called *Tosca Alemba* for reasons that will become clear, though some more general name might be appropriate when it is fully developed. This article describes some of the acoustic problems involved in the design, and the way in which they were solved.

2. CONCEPT OF THE INSTRUMENT

The *Tosca Alemba* had its genesis in another percussion instrument simply called the *Alemba* which was developed by one of us (MH) more than ten years ago. As described in an earlier publication [1], the *Alemba* consisted of a set of tuned triangles with one apex open, each coupled to a quarter-wave tubular resonator by a taut cord which drove a mylar diaphragm covering one end of the resonator. The length of each resonator was chosen so that its frequency matched that of the lowest vibrational mode of the triangle to which it was coupled, and this then defined the nominal pitch of the note produced. The triangles were initially equilateral, and the bend radius of the corners was adjusted empirically to give the best sound. It was later found, again empirically, that by lengthening the middle side of the triangles two of their modes could be brought into nearly octave relationship – a frequency ratio of 2:1 – with a consequent improvement in sound quality.

The vibrational modes of the *Alemba* triangles have been discussed in some detail by Dunlop [2,3] who used a finite-element method to calculate the vibration frequencies of a range of isosceles triangles with the apex open but with a variable radius of curvature at the two other corners. From calculations and measurements he showed that the empirically designed triangles had mode frequencies in the approximate ratios 1.0, 2.0, 2.35, 3.0, 3.6 and 4.9. The second mode (the octave 2.0) is well tuned, as is the fourth mode (the twelfth 3.0). The third mode is a somewhat flat-tuned minor tenth (ratio 2.35 instead of 2.4) which does not match well with the sharp-tuned sixth mode (ratio 4.9 instead of 4.8) an octave above it. The fifth mode (ratio 3.6) is similarly not very concordant.

The *Alemba* produced an exciting new sound and succeeded in many ways in reaching its design objectives. The first version of the instrument produced was a medium-pitched treble with a range of two and a half chromatic octaves from C_3 to F_5 or 130 to 693 Hz. (The pitch notation used here is the American standard, in which the lowest C

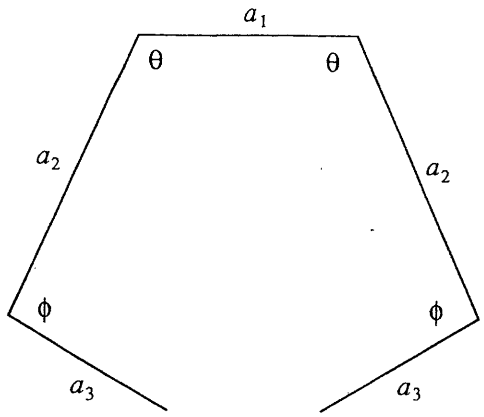

Figure 1. General shape of a pentangle, showing the adjustable parameters.

on the piano is designated C_1, all the notes in the succeeding octave are similarly given a subscript 1, the next octave a subscript 2, and so on. Middle C on the piano is C_4.) The base of each triangle was arranged to be horizontal, with the open apex hanging down, and the instrument was played by striking the base with beaters, the weight and softness of which could be chosen to give the desired sound quality.

Subsequently, at the suggestion of Sir Charles Mackerras, a bass version of the *Alemba* was built covering the octave C_2 to C_3, 65 to 130 Hz, with the objective of providing orchestral bell sounds for Berlioz' *Symphonie Fantastique*. While the sound was full and pleasant, the inharmonic ("out-of-tune") higher modes were judged to be too prominent for the instrument to be really satisfactory. It was the stimulus of solving this problem that prompted the design of the present instrument.

To provide the freedom necessary to tune the frequencies of the higher modes requires the introduction of more adjustable geometric parameters in the design, and it was proposed, on aesthetic rather than acoustical grounds, that this should be done by replacing the triangle with a pentangle, again with one open vertex. Again for aesthetic reasons, it was proposed that the pentangle have reflection symmetry, as shown in Fig. 1. For a given musical pitch, and thus total length of rod, there are two side-length ratios a_2/a_1 and a_3/a_1 and two corner bend angles θ and ϕ available as parameters, if the pentangle is not required to nearly close at the open vertex. This compares with only two adjustable parameters for the triangle problem at this level, though in fact the triangles in the *Alemba* were required to nearly close, thus leaving only one parameter. In both the original and the present designs, the bend radius at the corners was taken as a further parameter, though in the pentangle case it was treated as a secondary, rather than a primary, variable.

3. THE TUNING PROBLEM

Since our aim was to design an instrument with a rather low-pitched fundamental, it would have been convenient to base the pitch on the lowest mode of the pentangle, as in the original *Alemba*. This first mode is not satisfactory as a basis, however, since its frequency is too far separated from those of higher modes to produce a coherent tone quality. For this reason the second mode frequency was taken to define the nominal pitch of the pentangle. The tuning problem is then to adjust all the available geometric parameters to achieve a set of overtones in nearly harmonic relationship to this basis mode frequency.

A "brute force" approach to the tuning problem, using for example a finite-element approach and some global procedure to search for solutions giving frequencies in nearly integral ratios, was quickly seen to be impractical because of the volume of the four-dimensional parameter space to be searched. An altogether simpler approach was therefore adopted. This has been described in detail elsewhere [4] and will be only sketched here.

With four available parameters, in addition to the total rod length, it should be possible to tune the frequencies of four upper modes relative to the nominal second mode, as well as to adjust the basic pitch. To produce a bell-like sound that is musically concordant, we must insist that these upper modes are 3, 4, 5, and 6, since any badly tuned low mode will inevitably degrade the sound quality. Mode 1 for a bent bar lies at about one-third of the frequency of mode 2 and we can almost ignore it, since we can arrange that it is poorly radiated in the final instrument. It takes the place of the "hum" tone of a church bell, which is similarly not part of the main sound.

In a Western church bell [5] the important modes in order are the hum (frequency ratio 0.5), the prime or fundamental (1.0), the minor third (1.2), the quint (1.5) and the octave (2.0), although higher modes continue in roughly harmonic progression. For a bell with fundamental pitch C_3, these pitches would be C_2, C_3, $E\flat_3$, G_3 and C_4. The minor third component is characteristic of Western church bells, and we should try to design it into our pentangle – bells with a major third instead sound altogether different. The other important characteristic is the close frequency span covered by modes 2, 3 and 4. It turns out not to be possible to bring successive low modes of a bent rod into such close relative proximity, so that we must be satisfied with a wider spread.

To simplify the calculation, we first made the initial assumption that the rod from which the pentangle was to be constructed is thin – a quite good approximation – and the corners of the pentangle ideally sharp. With these assumptions it is possible to formulate and solve the in-plane vibration problem exactly and to determine all the mode frequencies for a given shape. The computational strategy adopted was to make a selection of well spaced guesses for two of the parameters and to search for values of the remaining two that gave reasonable approximations to integer-related frequencies for modes 2-6. Interpolation then suggested the regions of parameter space for further investigation. This strategy greatly reduced the computational problem so that it was easily solved on a personal computer. Just three acceptable shapes were found.

Since the pentangle was to be produced by physically bending metal rod, it is not realistic to assume ideally sharp corners. Indeed the sharpest reasonably attainable bend

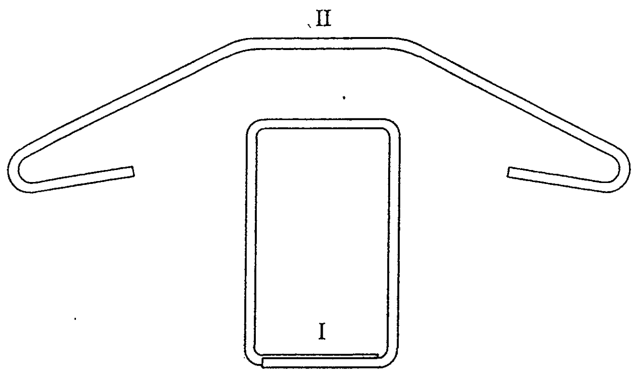

Figure 2. Two practical shapes for tuned pentangle vibrating elements.

corresponds to bending the rod around itself, and even less extreme bends are desirable in practice. A finite element program was therefore used to refine the solutions arrived at from the sharp-corner approximation and to turn them into practical designs. This eliminated one of the initial shapes, for which the bends were too extreme, and left the two shown in Fig. 2. Pentangle I is nearly rectangular, with the terminating sides overlapping, so that they must be bent slightly out of plane, while pentangle II looks rather like an open coathanger. (It has been suggested that it should be called a "boomerangle" to confer an Australian flavour!).

TABLE 1. Mode Frequency Ratios

Pentangle I (ideal)		1.00	2.00	3.00	4.80	6.00
Pentangle I (calculated)	(0.35)	1.00	1.96	3.05	4.82	6.13
Pentangle I (measured)	(0.35)	1.00	2.01	3.05	4.79	5.93
Pentangle II (ideal)		1.00	1.50	2.00	3.00	4.80
Pentangle II (calculated)	(0.32)	1.00	1.50	1.99	3.04	4.76
Pentangle II (measured)	(0.33)	1.00	1.49	1.96	3.05	4.75

The calculated and measured mode frequencies for the two shapes are given in Table 1. It is clear that we were able to achieve quite closely concordant frequency ratios, including the desired minor third (ratio 4.8), and that the experimental frequencies agree very well with those calculated. The pitches of the partials in the sound of pentangle I at a nominal pitch of C_3 are approximately ($F\sharp_1$), C_3, C_4, G_4, $E\flat_5$, G_5, while those of pentangle II are (F_1), C_3, G_3, C_4, G_4, $E\flat_5$, the first mode pitch (in brackets) not being really relevant.

The out-of-plane modes are quite inharmonic in frequency relation, which is actually an advantage since it gives the performer the ability to alter the timbre of the sound by striking directly or obliquely. After subjective acoustic evaluation, pentangle II was judged to give a better sound and was adopted for further development.

4. THE INSTRUMENT

The scaling problem for the pentangles is quite simple. We can either scale both the linear dimensions of the pentangle and the diameter of the rod together, in which case the frequency scales inversely with the length of the rod, or we can keep the rod diameter fixed and scale only the pentangle dimensions, in which case the frequency scales as the inverse square of the length of the rod. We adopted the second alternative, since it is much more economical of materials, though for an instrument with a really large compass some step-wise scaling of rod diameter would be desirable.

Because the rod from which the pentangles are made is only 12.5 mm in diameter, their radiation efficiency is very low at the frequencies of modes 1 to 6. Some sort of radiating structure is therefore required to couple the vibration of the pentangles to the surrounding air. Various possibilities were considered, including individual tuned pipe resonators, as in the *Alemba* and various types of tuned or untuned soundboard resonators. While resonant pipes have the advantage of being tunable to the individual pentangles, they are necessarily large and cumbersome for a low-pitched instrument. We therefore decided to use some form of soundboard radiator and to construct an instrument with a full chromatic octave of pentangles E_2 to E_3 to cover the requirements of the score of *Tosca.*

The design problem for a soundboard radiator for the combined pentangles is closely similar to that of the design of a harpsichord or piano soundboard. The soundboard resonances must be well distributed over the full compass of the fundamentals and upper modes of the pentangles, and it must be possible to provide a coupling that will drive it efficiently. The soundboard as finally designed by Graham Caldersmith was enclosed on its lower surface, to give adequate low-frequency radiation from its rather small size, and cross bracing was glued to its underside in a pattern designed to give an appropriate distribution of resonances, as checked by measurement. The soundboard tapers from bass to treble, and the cavity volume is an integral part of its design. The instrument is shown in general view in Fig. 3.

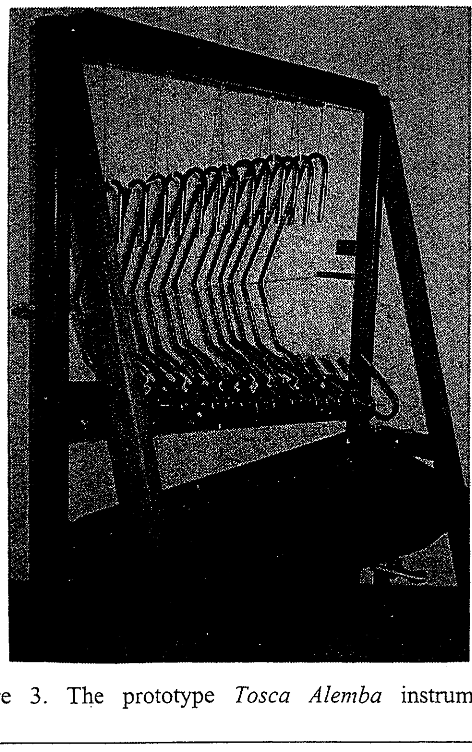

Figure 3. The prototype *Tosca Alemba* instrument.

Each pentangle is coupled to the soundboard by an elastic cord, similar to a guitar string, connecting one of its sides, near a corner, to a point on a line offset from the mid-line of the soundboard. This configuration provides efficient driving of the soundboard while the point of attachment to the pentangle can be adjusted so that the vibration of the pentangle is not too quickly damped. The elastic properties of the linking cord are such that it damps the highest frequencies of the vibration and makes the sound more mellow. The whole design is ergonomic, so that the player can strike the pentangles conveniently and see the conductor through the upper part of the instrument. In a refinement of the instrument we have now provided dampers, operated by a pedal, that can stop the sound quickly, as in a piano.

5. CONCLUSIONS

The success of a musical instrument depends not so much upon its technical virtues as upon its musical effectiveness, and this can be judged only by performers and composers. The *Tosca Alemba* instrument produces a new and interesting deep bell-like sound at a loudness that is adequate for chamber music or a small orchestra. For large groups it would probably require some form of amplification, which certainly detracts from its integrity as an acoustic instrument and raises the question of using a completely electronic synthesiser instead. However it does have the major advantage that its timbre can be controlled over quite a large range by the player – by using beaters of different weight or hardness, by varying the position of the strike, or by using an oblique strike to excite out-of-plane modes. It is this sort of flexibility that appeals to musicians, who interpret a musical score rather than simply acting as technicians.

A prototype of the instrument has now been built and will soon be available for evaluation by the musical community. Following that, the design will certainly be refined in detail before it is settled. We believe the instrument has an interesting musical future.

ACKNOWLEDGMENTS

It is a pleasure to express our appreciation to those who have helped with the development of this musical instrument. In particular we thank Paul Drew of the CSIRO Division of Applied Physics who made and tested all the pentangles over a period of many months with one of us (MH) as technical assistant, and to Graham Caldersmith of Canberra who designed and built the tuned soundboard, the casework and the damping mechanism. Without them the instrument would have remained simply an idea in the minds of its inventors!

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