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My interest in the classical guitar was aroused six years ago, and the absence of any rational literature on guitar acoustics stimulated me to make my own investigation. I wondered: was it possible that in spite of centuries -- even millenia -- of development, the guitar might not have reached an apex of design perfection? My answer to this question was an immediate yes. Even not knowing at that time the history of the instrument, a first examination of the interior of the guitar convinced me that by some strange accident of history, the traditional design arrived at for the classical guitar would tend to make it an inhibited instrument.

Initially, applying the ideas of theoretical mechanics suggested that one effect on guitar acoustics might be in a greatly increased power of the instrument. But as the project developed, the more important aims of control of tonal quality and balance of acoustical response (relative to the human hearing curve) seemed realizable. Later it became apparent that even the wave-form for sound generation (onset transient) could be brought rationally under control.

In taking up the project seriously, I realized that one must approach the hazardous task of the revision of established musical instrument design with the aid of the most skillful possible professional advice. The greatest guitar virtuosi were sought out for criticism of tonal quality and acoustical balance. Experts in guitar history and esthetics were consulted for criticism of form. Virtuoso craftsmen were involved in advice on construction. Experts on engineering acoustics and on the psychology of hearing were beseeched for advice on the objective measurement of sound and on auditory perception according to the best scientific criteria.

I have been most fortunate to have the matchless critical advice of Maestro Andres Segovia on numerous occasions; that of Vladimir Bobri, editor of the Guitar Review, on countless aspects of guitar esthetics; the cooperation of E. E. Watson on acoustical measurements of the guitar; and the cooperation of a number of highly competent luthiers, notably Jose Fernandez and Richard Schneider, on guitar construction. The constant interest of Sophocles Papas exerted a catalytic influence on the project. The daring cooperation of several concert guitarists, especially Mario Abril, in giving public concert-demonstrations added momentum to the project.

Physicists seem never to have been of much help in the design or perfection of musical instruments. Why is this? Firstly, in the case of most instruments, perfection of the instrument by trial and error methods by great craftsmen -- in constant interaction with virtuoso musicians -- was already achieved in many cases when many developments in physics were still in their infancy. Secondly, even today, although theoretical mechanics is a very highly developed science, the "physics of string instruments" as presented in texts and even research literature, is largely restricted to the physics of vibrating strings. Although diaphragm vibrations are described in abstract terms, no one seems to have troubled to consider the interaction of the string-bridge-soundboard-cavity combination. A coupling theory was missing. It is just this kind of theory of coupled oscillators which is a natural one to consider on the basis of theoretical mechanics and which it seemed necessary to apply to the string-soundboard instrument. Thirdly, a knowledge of the mathematical solutions and physical laws for theoretically idealized objects is a very long way from the detailed application of these theories to the practical building of musical instruments, and the evaluation of their esthetic qualities. Thus, the application of theory requires great intuitive compromises in going from the simple models of mechanics to the complex reality of the actual instrument. This step is as indispensable as the previous one of recognizing the appropriate theory, and can lead one to follow many alternate paths -- including treacherous and unrewarding ones. Perhaps in my case my training in physical chemistry rather than in theoretical physics better prepared me to cope with compromises in the fact of complexity, rather than accept defeat.

THE SOUNDBOARD WITH RADIAL BRACING

The heart of the guitar is the soundboard, represented mainly by the face of the lower lobe, to which the strings are coupled via the bridge. Until a century ago -- when the guitar was a sweet but feeble accompaniment instrument rather than a potent solo instrument -- the soundboard of the guitar was crossed by transverse bars (wood stiffening bars glued to the underside of the top perpendicular to the wood grain, or parallel to the bridge).

About a century ago Antonio de Torres introduced the expanded guitar body, a greater string length, -- and a fan array of seven bracing bars glued to the underside of the top (passing under the bridge and approximately parallel to the wood grain) -- the traditional classical guitar of today. These "resonance bars", being entire uninterrupted bars, would by their stiffness tend to oppose the very motions known to be characteristic of plate oscillation (normal modes). So at the same time that the resonance bars offer a coupling of the bridge rocking motion with the whole soundboard, they would serve to limit the amplitude of the very same motions. Torres left no writings on his work. It seems probable that he emulated the "bass bar" of classical violin construction in introducing seven resonance bars into the guitar, since the violin "bass bar" does strengthen low frequency resonance. But whereas the instruments of the violin family are structured to be acoustically highly asymmetrical internally, Torres made the guitar soundboard perfectly symmetrical. Most builders have followed Torres religiously in the century since his singlehanded advance.

Certainly many fine guitars have been built to the Torres pattern, in spite of the severe compromise that it set for guitar function. This compromise is apparent in acoustical measurements, and in the delicate margin available to the craftsman, between a responsive guitar and an overly delicate one. Unlike the violin family, there are no very old guitars in concert use today. The luthier faced with the problem posed by Torres bracing can gain power by a reduction of bar dimensions and top thickness -- until he approaches the danger point of fracture. The sight of guitar tops distorted by tension is all too familiar, not to mention those split beyond saving. Perhaps worse than this hazard is the loss of tonal quality and depth with increased lightness of construction -- seen most forcibly in some delicate Flamenco guitars.

The knowledge of the normal modes of vibration of circular plates and their symmetry properties (they are given in Helmholtz, <u>Sensation of Tone</u>, and in most books on acoustics and vibration physics) suggested that entire bars would be inhibitory. Initially, merely severed bars were considered; that is, bars radiating outward from the bridge to the edges of the soundboard; by proper shaping, these could increase the amplitude of motion of the top, and hence the power and the resonance time. However, realizing that the frequencies of the normal modes vary inversely as some power of the diameter of a circular plate, a graded structure was introduced. That is, for low frequency coupling, long bars were used on the bass side, and on the treble side shorter bars were used for high frequency coupling. In effect, this shifted the origin of the frequency spectrum of the top plate zonally, extending its response range. Since the guitar covers the range of about four octaves, a high frequency plate of somewhat less than one-half the diameter of the entire diaphragm was structured, for an arbitrary boundary condition. Thus the soundboard was made acoustically highly asymmetric. In the latest models, the resonance bars are graded continuously from the bass to the treble side. Since the bridge had primarily a rocking motion, a transverse bar was introduced with confidence directly under the bridge fulcrum (the saddle). No loss of power ensued, and tuning stability and mechanical stability of the top were assured.

It was then discovered, in consultation with musicians, that a variation in the onset transient could be obtained by altering the shape and distance of overlap or approach of the resonance bars to the bridge profile. Thus a tympanic, rapid, rise of wave-form could be produced, or a gradual onset with greater tonal purity could be generated -- at the control of the builder, and to the taste of the musician. Too slow an onset transient would of course lead to a loss of articulation. Control of this feature in traditional construction patterns is negligible. Furthermore, the radial bar pattern lends itself to shaping and length adjustment in the finished instrument; accidental undesirable resonances can be shifted or altered to some degree.

IMPEDANCE MATCHING BRIDGE

An early study of the role of the bridge in coupling string motion to soundboard motion led to consideration of bridge shape as a variable. The bridge has a rocking motion, whose amplitude is a function of frequency, so that the standard bar bridge is again a compromise. Ideally, the bridge, for mechanical impedance matching, should be widest at the bass end, and narrowest at the treble end. We can imagine the most favorable soundboard-driving with a high-amplitude, slow motion at the bass register, and a low-amplitude, rapid motion at the treble register. This ideal bridge is being developed in the latest work for maximum efficiency as a concert model.

As an artistic compromise, the rounded profile bridge design outlined roughly in the motif at the head of this brief essay is the one used in the standard Kasha Model. This feature is the only externally visible design change. When executed well in ebony or rosewood by a skillful craftsman, the new bridge impresses afficionados of the guitar with its dynamic, asymmetric beauty. The curves fit the guitar esthetics well, and the standard bar-bridge then begins to appear as a non-conforming anomaly. A split bridge was arrived at for independent coupling of treble and bass strings to corresponding zones of the soundboard.

As an ultimate and artistically radical design, the angular profile bridge outlined in the motif was developed. With this bridge, all traditional artistic design elements are open to reconsideration and development.

OTHER DEVELOPMENTS

Acoustical measurements on the earliest series of guitars, made by several builders to the designs described, showed the effectiveness of the radially-braced soundboard and the impedance-matching bridge combination. The overall general and quite reproducible characteristics were (a) a more resonant and powerful guitar, even with more substantial construction, and (b) a better acoustical balance, relative to the human hearing curve (Fletcher and Munson curve).

As the approximately 25 models were produced and tested, over the last six years, more and more improvements were introduced. With most of these, quite satisfying advances in sound production and quality resulted. It must be considered that all fine craftsmen experience a quality distribution curve for the result of their application of skill to the materials and design employed. Some accidentally ineffective guitars may result, the average quality depending on his virtuosity as a builder, and occasionally the guitar of his dreams may come out. The aim of the present design project has been to offer to the guitar builder a rational means of shifting his average guitar quality to a higher level, and to open the door to a perhaps undreamed-of level of guitar building achievement.

In all of the Kasha Model guitars an inertial mass (250 g. lead weight) is embedded in the upper neck, for increased sound power. The string, being a <u>real</u> oscillator, instead of an ideal one, has an end stiffness which serves to provide a mode of coupling to its mounting. In order to transmit a maximum amount of energy to the bridge and soundboard, instead of to the neck, the inertial load was introduced. The increased weight, counterbalanced by a tail-block weight, lends stability to the guitar on the player's lap.

Giving a complete functional analysis to each individual structural component of the guitar, has led to substantial improvements of many other structural features. Instead of treating the guitar body as simply a box, every structural member was studied for possible acoustical maximization. For example, the back of the guitar was redesigned as a vibratory component, considering the normal modes of the entire guitar body, instead of the approximation of the vibrating diaphragm alone. In the most advanced models some 20 new features or modifications were introduced.

The Weber-Fechner law of response vs. stimulus for human perception applied to hearing implies that the least noticeable difference for loudness perception is an average 24%. Even though a 20% improvement in sound production would be considered as substantial by the engineer or physicist, such an improvement would not be audible. Therefore, it is necessary to make instrumental improvements additively, so that the summation effect can be detected and evaluated. The Standard Kasha Model uses the three most important changes in design described above. In the advanced Model, in which everything is maximized for the concert performer, all 20 construction changes are incorporated It is natural that such variations greatly complicate the task for the builder, leading to an increased cost. However, compared with the violin family, guitars are certainly not prohibitively expensive. All musicians, professional and amateur, will appreciate the gain in quality, power, and total freedom from distortion under fortissimo playing, as well as responsiveness.

The aim of this project has been to make it easier for the craftsman to produce exceptional guitars by today's standard. The high consistency of the results shows the new design does have this function. In the Standard Model it was also an objective to preserve the traditional dimensions and appearance as much as possible.

A Concert Model (Long Model) is being developed, however, in which acoustical considerations are given complete preeminence. This has resulted in a guitar which departs substantially from the traditional guitar in general shape and appearance, although not alarmingly so. The player's mechanics are unaltered. This instrument is esthetically extremely pleasing to the builder, Richard Schneider, who has demonstrated a great capacity for innovation and interaction with me, as the designer. The new concert model is also extremely pleasing to me, and seems to reinforce the adage that function can dictate optimal esthetic design.

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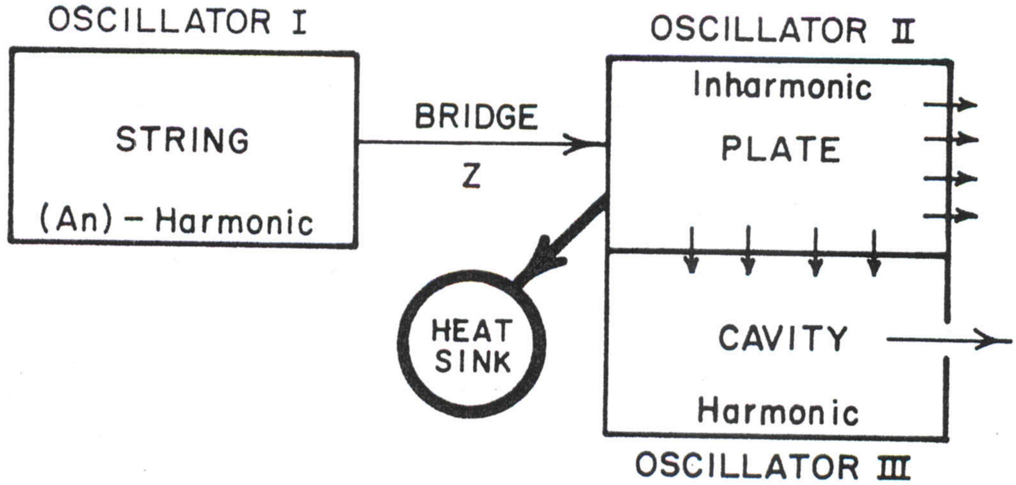
Edition 2

September 15, 1971

MODEL FOR STRING INSTRUMENTS



Information on Builder's Kits and Blueprints:
KASHA MODEL
3260 Longleaf Road
Tallahassee, Florida 32304

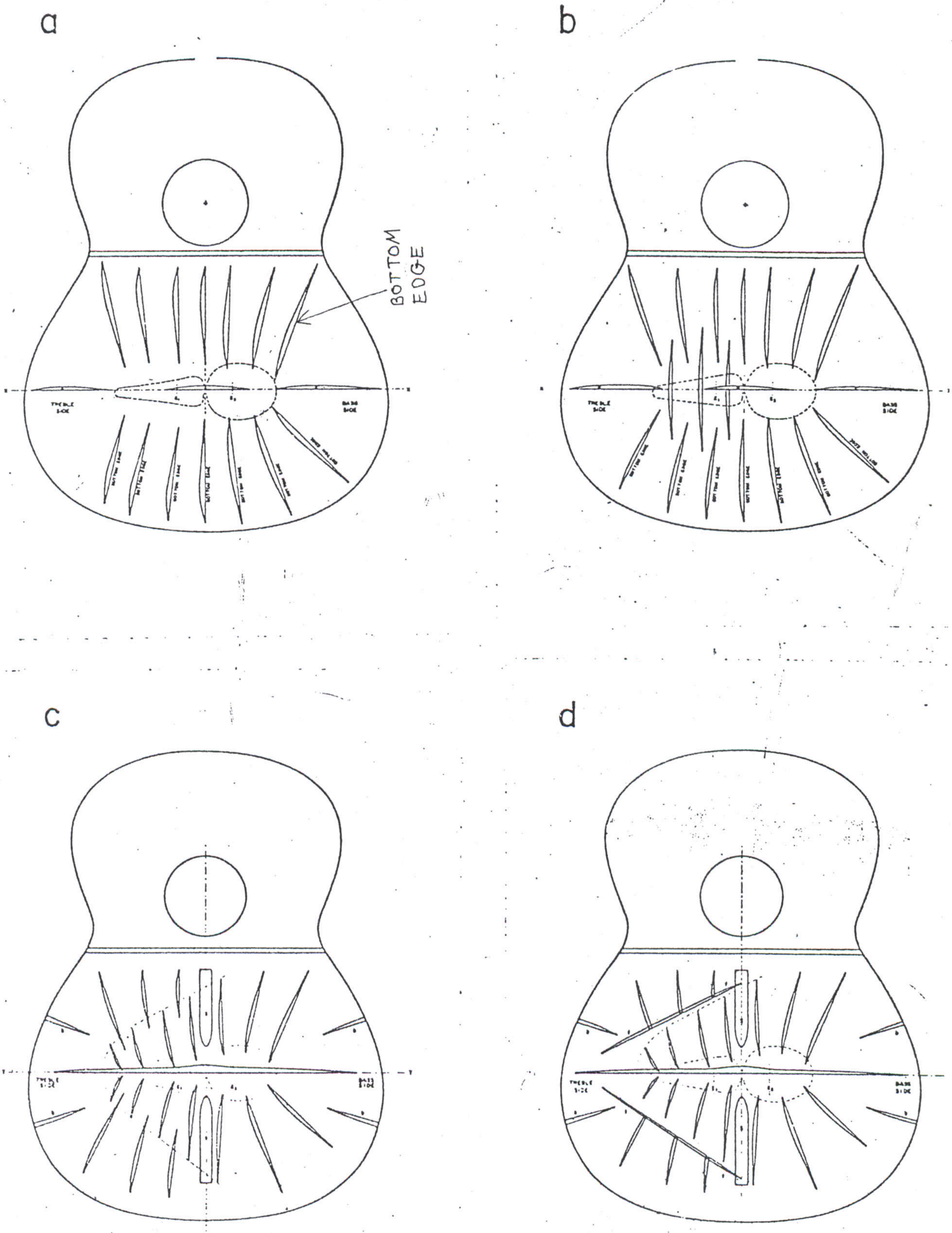


FIG. 17 EVOLUTION OF KASHA MODEL BRACING PATTERNS