Inharmonicity of wound guitar strings

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Wound guitar strings are known to "go dead" after several hours of playing. Increased inharmonicity of string partials is thought to be the primary contributing factor, making exact tuning of strings impossible. Increased inharmonicity with age is mostly due to changes in mass distribution and internal stresses, rather than changes in stiffness. String aging can be artificially induced by repeated stretching and relaxing of a new string. Measurements of the frequencies of the first ten partials in standard brass-wound steel guitar strings show that inharmonicity is significantly increased by repeated stretching. The inharmonic effect of stretching can be greatly reduced if strings are stress-relieved by heat after winding.

It is well known that steel guitar strings have a rather limited life time. In professional use they may not even last through an entire concert. Well before a string actually breaks, its mechanical properties change with age, causing it to "go dead", "loose bite", or making it hard to tune. This study is an experimental investigation of the physical meaning of string aging and of what can be done to extend string life.

Jont Allen reported a study in the Catgut Acoustical Society Newsletter a few years ago in which he compared new and aged wound guitar strings. Because inharmonicity seemed to be the principal problem with tones from old, worn out guitar strings, and since bending stiffness of a string is the prime contributor to string inharmonicity, it was thought that aging would perhaps be synonymous with changes in bending stiffness. Allen found, however, that bending stiffness does not change, but rather that damping increases with age, shortening the sustain of the higher partials. In the present study we have found supporting evidence that this does indeed happen, but that there is also a systematic change in the inharmonic relation between partials.

Our study employed brass-wound E strings, made available by National Musical String Company, which are normally tuned to 82.5 Hz. Measurements were performed with a new string strung on a solid-body electric guitar (modified Gibson SG model). After measurements were made the string was over-tuned by a fourth (pitch ratio 4/3, tension ratio 16/9), which brings it close to its breaking point, and relaxed. This process was repeated 20 times.
Although we have no direct evidence that this kind of torture is a good model for natural string aging, it did result in noticeable and hopefully relevant changes in string behavior. The advantages of this method are that it works fast and allows comparison of string behavior on the same string and the same instrument. All measurements were repeated immediately after the torture procedure, that is, if the string survived.

Measurements consisted of plucking the string at approximately one-tenth of a string length measured from the bridge and subjecting the output waveform of the pickup to (a) a digital time-varying harmonic analysis on the first ten partials and (b) a measurement of the exact frequencies of the first ten partials. The time-dependent harmonic analysis basically divides the relevant spectral range in ten bands and computes for each short time period the average power in each band. This way a time-varying power spectrum is obtained that shows the intensity of each harmonic in decibels as a function of time. The second measurement was done by filtering the plucked string sound through an HP wave analyzer tuned to the appropriate partial, and steadying an oscilloscope display with an external synch signal which could then be counted.

Figure 1 shows time-varying spectra from two new and quick-aged strings, which we will refer to as #1 and #2. In string #1 the first five harmonics seem hardly affected by the aging process, but harmonics higher than five seem somewhat suppressed or decay quicker after quick-aging. This difference is much more pronounced in string #2.
This finding supports Allen's conclusion that there seems to be increased internal damping in aged strings. It may be caused by loosening of the wrapping. Both strings #1 and #2 were run-of-the-mill brass-wrapped steel strings without special treatment.

Figure 2 shows the results of precise frequency measurement of respective partials of the new and quick-aged strings. For each harmonic number, the difference between the measured frequency and the appropriate multiple of the fundamental is plotted in cents, where one cent is one-hundredth of an equally-tempered semitone. The top panel shows inharmonic deviations for string #1, the solid curve before, the dashed curve after repeated stretching. The middle panel shows similar results for string #2.

Fig. 2

Inharmonic deviation in cents for three kinds of strings
There are two important features in these data. First of all, deviations from harmonic frequencies are always positive, i.e., harmonics are stretched. This is consistent with Allen's measurements and also with the notion that bending stiffness is the dominant source of inharmonicity. Secondly, contrary to Allen's results we find that inharmonicity does increase significantly after artificial aging. This seems to suggest that stiffness has changed. We believe, however, that things are not as simple as that. Bending stiffness of a wound steel string is largely controlled by the stiffness of the core wire. Since this core wire was not stretched beyond its elastic limit, it is unlikely that its bending stiffness would have changed. There are other potential sources of string inharmonicity, such as internal stresses caused by the brass wire being forced around the steel core. The distribution of such forces, which is some random function of the wrapping process, may easily be changed by stretching the string several times. Moreover, windings may actually slip in the stretching process and redistribute the mass of the wrapping wire to some degree, causing more inharmonicity.

This hypothesis is supported by the measurements shown in the bottom panel of Fig. 2. They are the average results of three identical strings that had been specially treated. Brass wire was wrapped around a steel core of hexagonal cross section to insure a better grip and less slippage. Furthermore, the strings were stress-relieved after wrapping by heating them to an appropriate temperature. One can see from the results that reduced internal tension leads to significantly reduced inharmonicity in the new strings, and also to reduced inharmonicity increase as a result of over-stretching.

One should keep in mind that repeated stretching is at most only a partial simulation of real string aging. When strings are played, foreign material will build up between windings where fingers often touch the string, and windings wear off where they are rubbed over the frets during note-bending. Both processes result in uneven mass distribution and therefore inharmonicity. It is obvious that stress-relieving the strings will not solve those problems. Finally it should perhaps be pointed out that perfect harmonicity may not be synonymous with excellent
tone quality. It is possible that some inharmonicity in the higher overtones may contribute to the liveliness of a guitar tone, although hard evidence of this has never been presented. On the other hand, the first eight to ten partials in a complex tone are the main contributors to the pitch percept of the sound, and the closer their harmonic relation is, the clearer pitch the sound projects. A close harmonic relation among lower partials also makes the guitar much easier to tune. We believe therefore that it is a reasonable objective in string design to try to achieve an as closely as possible harmonic relation between frequencies of the first ten partials.