Unfortunately, not all manufacturers of strings give information regarding the actual build of their strings. Tom Wheeler uses the heading "Welcome to Fantasyland" for the chapter on strings in his reference oeuvre "Guitar Book". And he continues: “Advertisements for string often bristle with misleading information; one almost forgets that the only serious path to a good sound is paved with auditory experiments”. Indeed – it ain’t easy. Gerken at. al opine: “phosphor-bronze strings sound a little more mellow that 80/20 bronze or brass strings”; in Day et al., it conversely reads: “Phosphor-bronze sounds more brilliant than bronze”. Both books were issued (in Germany) by the same GC-Carstensens publishers within only 2 years.

Often, the declarations about materials used flounder on the marketing primacy: brass (which is a copper-zink-alloy), for example, turns into “bronze”. The reason might simply be that brass is also the term for horn instruments … as played in that other kind of “band” … the one in the football stadium. Do guitarists seek association with that scenario? Probably not, the contrary may actually be true. *(The translator recalls Pat Metheny’s “Forward March” here ...)* So: “bronze” rather than “brass”. This ab-use has even migrated in German guitar-“literature”. Now, how do you call the winding made of “real” bronze (a copper-tin-alloy), then? Right: name it “bronze”, as well! Or maybe “phosphor bronze”, to distinguish it from the (boring) other “bronze”. Come to think of: the mentioning of phosphor is not necessarily off, because bronze tends to become porous … indeed, phosphor is added: has a cleaning effect and reduces the porosity, and the high hardness of Cu_3P brings more brilliance to the sound. How much P the manufacturers add – that remains shrouded in the mystery that is string marketing.

Similar vagueness is found in “pure **nickel** strings”. Strings made from pure nickel could never, ever withstand the high tensile load – you have to use steel. Only the surface (nickel plated) or the winding (nickel wound) may consist of nickel. The winding may be made from pure nickel or form nickel-coated steel. The manufacturers are reluctant to hand out the specifics, though. Only the advertisement for most recent development is clear about which side one’s bread is buttered on: “special strings for lefties” …

3.2 The loudness of the strings

If you exchange on your guitar the 009-string-set for an 011 one, will it sound louder? Practical experience says: yes – theoretical considerations advise caution, though. First, we should look at a meaningful intermediate quantity rather than the loudness that is difficult to establish. Using the AC-component of the force at the bridge (acoustic guitar, pickup built into the bridge) come to mind, or the induced AC-voltage (magnetic pickup). Keeping the boundary conditions constant (!), there is no way around realizing that neither the bridge-force, nor the pickup voltage includes any dependency on the string diameter.

The **force at the bridge** first: the excitation force transferred to the string as it is plucked may be modeled as sum of two sub-components of equal value causing transversal waves running in opposite directions (Chapter 2). These two waves superimpose at the bridge with equal phase: the force at the bridge (only the AC component is of interest here) thus corresponds to the plucking force – that’s independent of the string diameter. Still, the diameter of the string has an effect on the sound because it affects the transverse stiffness (see appendix), and thus the displacement of the string The heavier the string, the larger the plucking force for a given displacement can be, and the louder the guitar will sound – if the guitarist takes advantage of this. With *equal* plucking force, heavier strings bounce less (Chapter 1.5.3) and sound fuller. We could have analyzed the dependency of internal damping mechanisms and radiation losses on string diameter – but that had less priority and was put on the backburner.

In the **magnetic pickup**, the vibrating string induces an electrical voltage that is proportional to the velocity of the string. Redoubling the amplitude of the string displacement leads to double the velocity and thus to double the induced voltage – at least as long as we take the linear model as a basis. However, a number of other factors enter into the transfer coefficient of a pickup, as well: winding- and magnet-parameters, the distance between string and magnet, the direction of the string vibration, and the string diameter … to name but the most important ones. Our first considerations are directed to the induced voltage and its level.

The dependency of the pickup voltage on the diameter of the string was experimentally determined using a test bench fitted with a shaker. For all measurements, a Stratocaster pickup was deployed, with a string being sinusoidally moved up and down over its D-magnet at a frequency of 85 Hz. The direction of the vibration was along the axis of the magnet, with a displacement amplitude of 0,22 mm. Varying the amplitude between 0,15 and 0,50 mm gave no indications of any substantial non-linearities: the voltage remained proportional to the displacement in this range. The clear width between magnet and string was 2 – 5 mm; no abnormities could be detected for these distances. The pickup-voltage level changed with about 2,1 dB/mm for light strings, and with about 2,7 dB/mm for heavy strings. Solid strings with diameters between 0,23 and 0,66 mm yielded proportionality between pickup voltage and **cross-sectional area of the string**. Redoubling the string diameter quadruples the output voltage (all other parameters remaining constant).

The proportionality between voltage and cross-sectional area only holds for solid strings, though. In **wound strings**, the winding is magnetically not fully effective. In the experiment, the core wires of Fender strings type 150 (pure nickel wrap), type 250 (nickel plated steel wrap), and type 350 (stainless steel wrap) were compared. The core wires are hexagonal with a diameter of about 0,4 mm. In terms of figures, the winding increases the cross-sectional area by a factor of seven – the measurement shows merely double the voltage, though, for the core with winding compared to the core without winding.

Fig. 3.2 explains why the winding is so inefficient magnetically: the individual layers only touch at narrow fringe areas, and this is what predominantly determines the magnetic resistance (Hertzian stress). While a part of the magnetic flux will find its way without air gap via the helix-shaped path along the winding, this path is much longer and shows, relative to the core, a magnetic resistance larger by a factor of 10. The magnetic effectiveness of the winding depends, other than on the permeability, also on the mechanical tension in the winding. If all windings are densely and tautly placed next to each other, larger areas of contact result, with the string representing a smaller magnetic resistance. The annular area marked grey in Fig. 3.2 is to be seen as an equivalent: a corresponding hollow cylinder would have the same magnetic properties as the winding (measurement results from the Fender strings).

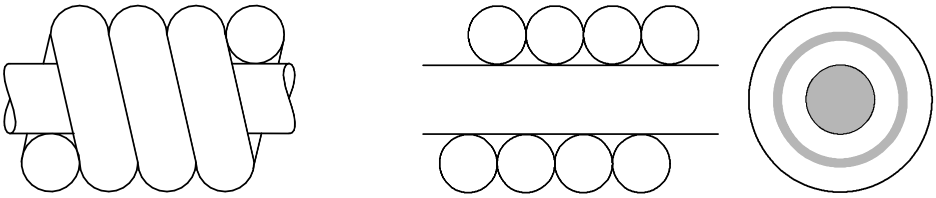

Fig. 3.2: Wound string: the areas indicated in grey on the right are magnetically effective (compare to Fig. 3.1) In contrast to the figure, the core of the Fender strings is hexagonal.

The **winding** of a string contributes to the sound in more ways than one: the *mass* of the winding increases the mass of the string, but it does so without substantially increasing the string stiffness. The *hardness* of the winding determines the harmonic content generated as the string bounces off the frets. The *magnetic* characteristics of the winding determine the (electric) loudness of the string. Now, **loudness** is a quantity that is not easily described and that depends on many parameters, e.g. on the levels of the partials that in turn may be traced back to the electrical partial-voltages generated by the pickup. Assuming a fretboard-normal string vibration, the voltage of the fundamental depends on the cross-section of the string, on the string velocity, and on the string-to-magnet distance. In the frequency range of the fundamentals, the transfer coefficient of the pickup is still substantially independent of the frequency and may be seen as constant (although it could well be modeled as frequency-dependent, see Chapter 5). The clear width between string and magnetic pole of the pickup is – for the time being – also seen as constant, so that merely string velocity and string cross-section remain as parameters to be considered.

The voltage of the fundamental is proportional to the particle velocity of the string (law of induction) and to the string cross-section (measurement results): $U \sim v \cdot S$. The string velocity depends on the fundamental frequency and the string displacement, the latter being traceable back to plucking force and transverse stiffness s_Q. For a constant distance to the bridge, the transverse stiffness is directly proportional to the tensioning force of the string. This force has similar values for all 6 strings.

Assuming a constant plucking force, we obtain for the string displacement ξ:

$$\left.\xi = F/s_Q\,; \qquad s_Q \sim \Psi; \qquad \Psi \sim S \cdot f_G^2\,; \qquad \right\} \qquad \xi \sim \frac{1}{S \cdot f_G^2}$$

The string velocity is proportional to the product of displacement and frequency. What therefore remains for the tension is a simple frequency dependency that is independent of the cross-section:

$$\left. v \sim \frac{1}{S \cdot f_G}; \qquad v \cdot S \sim 1/f_G; \qquad U \sim v \cdot S \qquad \right\} \qquad U \sim 1/f_G$$

If all 6 strings on the guitar were solid, and given the above conditions, the E_2-string would generate the quadruple voltage relative to the E_4-string. Because in each string the second harmonic is of double the frequency of the fundamental, the same relationship would be found here, as well. This simple consideration may not readily be transferred to *all* partials, but we can already say without diving into the depths of loudness-calculation that the bass-strings would be too loud in comparison to the treble strings. However, the wound strings are magnetically less efficient than the solid treble strings, and therefore all strings generate (via pickup, amplifier, and loudspeaker) a similar loudness as a first approximation.

Fig. 3.3 presents the dependency of the level of the fundamental on the frequency. This graph may serve as rough orientation regarding the loudness of the strings (although of course loudness and level are two different quantities). If all strings were solid, the dashed $1/f$-line would result. The measurement values (gathered with a Fender 150 string set: 042-032-024-016-011-009) are indicated as the bold line. All measurements were performed over one and the same magnet of a 1972-Stratocaster-pickup. The figure on the right shows the results taken from a typical bronze-wound string set (again measured with the Stratocaster pickup).

This figure is reserved for the print version of this book

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Fig. 3.3: Level of the fundamental of the 6 guitar strings (magn. pickup). Winding: nickel (left), bronze (right).

The ratio of core diameter to overall diameter presents a significant parameter of the wound string. For E_2-strings this ratio is in the order of 0,33, for G-strings rises to about 0,6 – with manufacturer-typical variations (Chapter 1.2). The winding-inefficiency is predominantly due to the geometry and can therefore not be influenced much via ferromagnetic parameters.

Comparative measurements on Fender E_2-strings of the types 150 (nickel-wrap), 250 (nickel plated steel-wrap), and 350 (stainless steel-wrap) yielded comparable voltage levels for the 150 and 350 types, with the type-250-string generating 1 dB more relative to this. About half of this efficiency increase could be attributed to the slightly larger core diameter. An unobtainably high precision would have been required to exactly research the underlying reasons: for a measurement accuracy of 0,1 dB, the core diameter would have to be determined (and maintained) with a precision of 0,6% – for a core diameter of 0,4 mm this implies a tolerance of 2,4 µm! Furthermore, the distance between string and magnet would have to be adjusted with a precision of 40 µm. While the latter requirement appears doable, it is certainly not trivial given a test bench made entirely of plastic components. Therefore, **tolerances** of some 10^{ths} of a dB have to be expected for all statements regarding levels.

The pickup-industry has already early on attended to the variations on string gauges; adjustable or different-length magnets were included in the pickups (**staggered Magnets**, Chapter. 5.4.6). However, apparently the differences are judged to be more on the insignificant side, because in many magnetic pickups the 6 magnets protrude to the same extent from the pickup housing. Be warned about unauthorized modifications, though: it is not advisable to move the magnets in old Fender pickups – the fine-as-a-hair winding wire is in direct contact with the magnet and can be damaged very easily. In modern pickups with a plastic bobbin, shifting the magnets should be possible but even in this case a consultation call with the manufacturer might be a wise idea.

Supplementing the measurement with the shaker, the levels of the strings were also subject to an auditory evaluation. A well-versed guitarist played a Stratocaster (flush pole-pieces) fitted with Fender 150 strings and did his best to pick the individual strings with equal force. With much effort, it was possible to detect any significant difference in the **overall level** between the D- and the G-string: the level of the G-string was about 4 dB higher relative to the D-string. Due to a lack of reproducibility, the level differences of the remaining strings could not be determined with sufficient accuracy. When playing regular lead and rhythm, differences were not noticeable. The D/G-difference was just about detectable – if one really concentrated on the task. However, as soon as the player directed his attention to the music to be played (this would be have to be seen as the normal approach), the differences between the strings did not stand out anymore. We did not further investigate whether there was any compensatory action in a senso-motoric control circuit, of whether the perceptional threshold had shifted.