4.11 Magnetic Field Forces

Magnetic forces are the most obvious effect of the magnetic field: If one places a *ferro*magnetic material into the field of a permanent magnet, it will be drawn towards one of the magnetic poles. Magnetic forces also act for *para*- and *dia*magnetic materials, however, they are barely detectable. Only when the string is composed of a ferromagnetic material its vibration can be effectively detected by a magnetic pickup, because only then will the string significantly change the magnetic flux, so that a sufficiently high voltage is induced. At the same time, however, the magnetic forces will change the vibration mode of the string – the generation of a voltage in the pickup is, thus, not free of retroactive effects.

Theoretical physics does not view the electrical and magnetic fields as independent and self-contained conditions in space, but rather combines both phenomena into a unique field theory. Forces between stationary charges have to be treated differently from charges in motion: a relativistic approach is necessary even for small velocities. However, for the pragmatist says that *veritable is only what is appropriate for the act* and he gains the winning tender, in this case. The unique field theory is elegant but, for the present considerations, classical electrical engineering theory is sufficient and describes – as shown in the following – the force effects as independent phenomena.

4.11.1 Maxwell's Force

A ferromagnetic string brought into a magnetic field experiences a magnetic force. Here, it does not matter whether the string approaches the north or the south Pole; in both cases it will be attracted. The larger the field strength the larger the attractive force. The force, however, does not generally act in the direction of the of the field strength – and likewise also not generally in the opposite direction. Most simply one can interpret the magnetic force as a surface force that affects the entire surface of the string. Hereby it is understandable why an iron ball will stay at rest if brought into a *homogenous* magnetic field: the drag forces acting on both halves of the ball are balanced and the resulting sum of forces is zero. The fact that an iron ball in the field of a horseshoe magnet is nevertheless attracted by one of the poles is due to the inhomogeneity of the field. Only in a very theoretical middle position could an instable balanced condition be constructed; in every other position one of the two forces dominates and will accelerate the ball. This is completely different for the Coulomb force (4.11.6): a charged Styrofoam ball will also be accelerated in a *homogenous* electrical field.

The magnetic force effect may be very obvious; however, it still remains difficult to understand its underlying mode of action. Around the beginning of the 19th century magnet scientists still had the opinion that magnetized bodies would act on each other by a **long-distance effect**. This fact, that even an intermediate vacuum could not prevent this long-distance effect, lead to the conviction that the intermediate space was not involved and that the magnetic forces would directly act on the bodies without changing the space in between. The first person to define the **concept of the field** was Michael **Faraday** at around 1830, which changes the space between the bodies by force lines (**near-field theory**): the space itself will now become the medium and transmitter of the force.

James Clerk **Maxwell** (1831 – 1879) extended Faraday's ideas into a comprehensive electromagnetic field theory. A field is assigned to every point in space, which is defined by its **field quantity**. For the magnetic field these quantities are the field quantities H and B. The permanent magnet of the pickup generates an electromagnetic field that acts on other bodies (e.g. on a string) and produces forces there. However, the now magnetized string will also produce a field that acts on the permanent magnet. The generation and changes of these fields happen in the pickup practically without delay.

A mechanical stress state can be assigned to every point in the magnetic space within a very general force effect theory. The theory of elasticity distinguishes between **normal stress** (force perpendicular to the area) and **shear stress** (force runs within the area). For example, if a steel cylinder is stressed in the axial direction a tensile stress is generated which will elongate the cylinder. At the same time it will become a little bit thinner, because a compressive stress acts in the radial direction (lateral contraction). On the other hand, shear stresses are generated by shearing-off a whisker, which are also called **shear strains**.

A general quantity for the characterization of the mechanical state of stress is the **stress tensor**: it describes the mechanical stress load that a differential small volume of the string is exposed to. By integration over all these string volumes (mathematically formulated by Gauss's integral law) one will arrive at surface forces that act in a radial direction with respect to the string's surface. Since two magnetically very different materials converge at the string-air interface, one can obtain a very simple approximation for the normal force per area (*F/S*):

$$\frac{F}{S} = \frac{B^2}{2\mu_0} \qquad \mu_0 = 1{,}26 \cdot 10^{-6} \, \frac{\mathrm{Vs}}{\mathrm{Am}} \qquad 1 \text{ VAs} = 1 \text{ Nm.}$$

The area-specific force is proportional to the square of the flux density. For B one has to take the value that will result at the string surface and not the value which will be measured without the string. The value at a distance of approx. 2 mm in front of a pickup magnet without the string will be 20 – 50 mT, while it will be approx. 200 mT including the string. The string, as a consequence of its good magnetic conductivity, "sucks" the surrounding field lines as it were and, thus, increases the local flux density. As a rough approximation one will get 48 mN for the magnetic force for a string area of 3 mm² and 200 mT flux density. A precise calculation is difficult, because in this case the three-dimensional field distribution in two non-linear media would have to be determined. In contrast, **measurements** convey a sufficiently precise picture: for this a magnetic pickup was moved towards a steel wire (0.7 mm diameter) and the resulting magnetic force was measured (**Fig. 4.49**). Forces of 10 to 40 mN are detected for common separations – a good confirmation of the theoretical estimation. For a typical humbucker (e.g. Gibson '57-Classic) the forces are smaller.

In comparison to the string tension force (50 – 200 N) the magnetic forces are very small; the lateral string displacement caused by them is less than 0.1 mm. Nevertheless, the effect of the magnetic field must not be totally ignored, because its stiffness changes the frequency of the string. The nearer the string comes to the magnet, the more it is pulled. The differentiation of this force/distance relation will yield a distance-dependent stiffness of –1 ... –30 N/m; in contrary to common springs it is negative. The numbers are to be interpreted as guiding value; the measurement precision is only moderate.

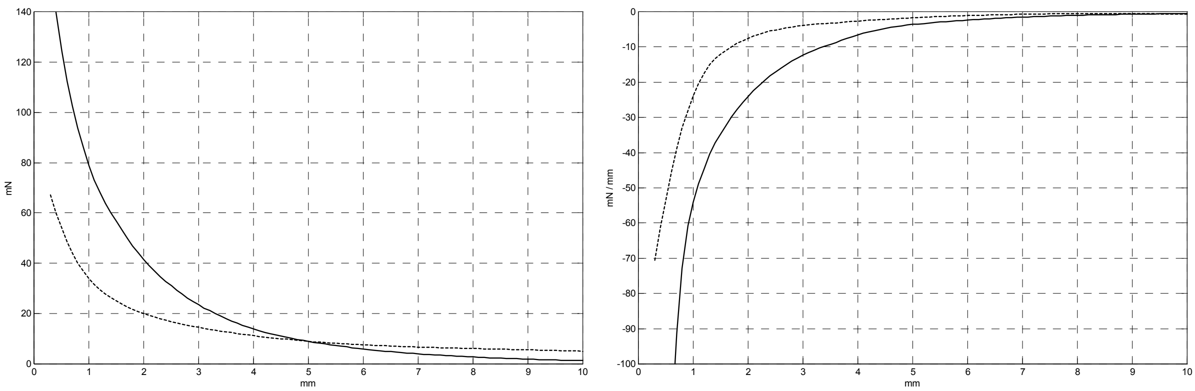

Fig. 4.49: Magnetic force as function of the clearance. Alnico-5, singlecoil (——), Gibson-humbucker (---). In the right picture the differential stiffness is shown as a function of the clearance.

However, the **negative magnetic field stiffness** not only affects the vibrations normal to the fretboard; for vibrations parallel to the fretboard the string/magnet distance is practically constant, the magnetic field stiffness is therefore negligible♣. For vibrations normal to the fretboard the negative field stiffness generates a decrease of the mechanical stiffness and, hence, a decrease of the partial tone frequency of the string. The effect is not dramatic, but audible for strong magnets: if the magnet is moved closer the tone frequency drops. However, every vibration of the string will occur as spatial wave, not as plain transversal wave. Even if a *plain* vibration is prevalent shortly after plucking, mode coupling in the supporting points and, last but not least, the magnetic field will cause a rotation of the original vibration plane. The rotation frequency is low (some Hertz) and beat-frequency-like **amplitude variations** will evolve in the pickup signal (4.11.3).

In this way the magnet does not just change the tone frequency but also the tone color of the vibrating string. Whether this is good or bad depends on subjective assessment criteria. Many guitarists have the opinion that the chorus-like beat frequencies of a Stratocaster belong to the typical sound of this guitar – as long as they are not too dominant. The assumption (or "certainty" of expert authors) expressed in several books that "the harmonics are slightly detuned in comparison with the fundamental*s*" is incorrect: the **fundamental** will be detuned the most. One can ask, since 2001, why it is suddenly referred to in the plural, and who feels that the announcement: "*further handbooks are in preparation*" is mere threat. However, this is just how they are, those string fundamentals.

4.11.2 Field-Induced Deviations of the Tone Frequency

When a magnetic pickup approaches a string, three effects can be anticipated: The **tone frequency** decreases, chorus-like **beat frequencies** evolve and the **amplitude** changes. The frequencies, especially the fundamental, will decrease due to the negative field stiffness, which can be audible for large values. The detuning between the fretboard-normal and fretboard-parallel vibrations induces beat frequencies; the altered frequency relationship between the partial tones in the subsequent non-linear systems causes additional partial tones, which can further increase the chorus impression. True damping, i.e. removal of vibrating energy, occurs only to a negligible extent. Firstly to the tone frequency:

♣ If the string is located substantially beyond the magnet axis, both vibrating planes are affected.