10.9.2 Tube-Watt vs. Transistor-Watt

Allegedly, tube amps are louder than transistor amps rated at the same output power. Before we discuss this topic on a scientific level, we first need to establish what exactly is meant with "this is a 50-W-amp". *Not* meant is the power consumption i.e. the power drawn from the mains. Rather, such a specification always refers to the output power fed to the loudspeaker. If the speaker impedance were frequency-independent and real, this power could be stated without any issue. However, the loudspeaker impedance is frequency-dependent and complex, despite the simple 8-Ω-label. In order to still be able to specify a number of watts, an ohmic resistor replaces the speaker, and it is for this resistor that the indicated number of watts holds. In other words, the manufacturer specifies that an amp generates e.g. 50 W at 8 Ω. This does not in fact tell us how much power this amplifier can deliver into an 8-Ω-loudpseaker, because an 8-Ω-speaker does not have 8 Ω at all frequencies (Chapter 11.2).

In an 8-Ω-resistor, an alternating current of the RMS-value of I = 2 A generates the RMS-voltage U = 16 V; the product of current and voltage yields the power: P = 32 W. In order to clarify that these are RMS-values, a tilde is often put over the formula symbols:

$$P = \tilde{U} \cdot \tilde{I} = R \cdot \tilde{I}^2 = \tilde{U}^2 / R ; \qquad \tilde{U} = \sqrt{P \cdot R} ; \qquad \tilde{I} = \sqrt{P / R}$$

For an RMS-current of 2 A, the matching current amplitude is $\sqrt{2} \cdot 2$ A (i.e. 2,8 A), and correspondingly the voltage amplitude of 22,6 V matches an RMS-voltage of 16 V. Multiplying the amplitude-values rather than the RMS-values yields double the power: a 32-W-amp turns into a 64-W-amp. This (higher) wattage specification is not in use in the professional audio technology – rather, the nominal power calculated from the RMS values is specified; in the example this is P = 32 W. What does this power depend on? Its factors are e.g. the squared RMS-voltage, and a more or less arbitrarily defined nominal resistor R that initially replaces the loudspeaker. The resistor is defined as fixed quantity in the data sheet; the voltage is, however, variable. So, for which drive-levels do we specify the nominal power? For studio- or HiFi-equipment, the largest voltage just below distortion level is used, or the voltage at which a certain total harmonic distortion (THD, to be specified) occurs: e.g. 32 W at 8 Ω and for k = 1%. For a guitar amplifier, such a THD-specification is not possible, and therefore – for a sine-shaped drive signal – the output voltage is visually judged to specify at which level clipping occurs. Again: for the calculation this limiting voltage may not be substituted into the formula because it represents the amplitude (i.e. the peak voltage). Rather, this limiting voltage needs to be divided by $\sqrt{2}$. Alternatively, the amplitude is used, and the calculated power is then divided by 2. As an example: for an 8-Ω-resistor, clipping occurs at 40 V. The resulting RMS-voltage is 28,3 V, and the power is calculated to P = 100 W. Alternatively: $40^2 / 8 / 2 = 100$.

Incidentally, it is not sufficient that a loudspeaker box connected to a 100-W-amplifier can withstand merely 100 W. Since guitar amps are typically overdriven, they generate more than the specified nominal power. Given that the nominal power mentioned in the above example is independent of the load, for a square-shaped signal the power would be double, i.e. 200 W! This is because square- and sine-shaped signals of the same peak-value differ by a factor of $\sqrt{2}$ in their RMS-values.

The limiting-voltage (i.e. the voltage at which the output voltage starts to clip) is, however, not entirely independent of the load because the internal impedance of the power supply is not zero. The **power supply** furnishes the operating voltage to the power amplifier – for a tube amp e.g. 450 V. This is a dc voltage the value of which depends on several parameters: on the mains voltage, on the power transformer, on the rectifier, and on the load. In the unloaded state, the operating voltage has its maximum value but buckles ("sags") under load, i.e. as the amplifier feeds power to the loudspeaker. This has a very simple reason: the current flowing to the power amp first needs to pass through the mains-transformer and the rectifier – and either of them causes a voltage drop. The exact voltage and current time-curves are anything but simple to describe (these are coupled non-linear systems), but we do not need to examine this very precisely here. With a load connected, the operating voltage buckles and decreases, e.g. from 450 V down to 400 V, or even down to as low as 360 V. Given a large mains-transformer and an efficient silicon-rectifier, the voltage drops only little; with a small transformer and a tube-rectifier the drop is larger – this is another genre-typical difference. Massive 100-µF-capacitors make the "sagging" (as well as the subsequent recovery) slower than the (from today's perspective) puny little 16-µF-caps. Here we actually may have a difference between tube-Watts and transistor-Watts: modern transistor amps often have very "stiff" power supplies, i.e. power supplies with a small internal impedance the voltage of which decreases only little as a load is connected. Tube amps (especially if they are from back in the day and carry a tube rectifier) have power supplies with comparatively larger internal impedance (see Chapter 10.1.6). Of course the two aspects are not necessarily connected to each other: a tube power amp could just as well include a power supply with low internal impedance – but in particular the legendary amps do not. For a guitar-note played after pause, the full charge of the power-supply-cap is available during the first instant. The limiting voltage may e.g. be 40 V yielding 100 W of nominal power into 8 Ω. However, the voltage buckles after a few milliseconds and the limiting voltage drops to e.g. 35 V. With the power being in a square-dependency to the voltage, the power decreases to 77 W. Measuring the nominal power with a continuous sine-tone yields the second value, i.e. 77 W. For a transistor amp fitted with a "stiff" power supply, the limiting voltage may decrease e.g. only from 37 V to 35 V, so that both amps have the same nominal power. For an impulse, i.e. as a string is struck, the tube amp does however have a higher power; in the example it is 100 W rather than 85 W. In case the limiting voltage of a tube amplifier does not only decrease by 12,5% but by 15% or 20%, these differences become substantially larger.

Thus, one difference in the power yielded by tube- and transistor-amps relates to the temporal behavior: the "attack" is delivered with more power in a tube amp. This holds for the generic circuits – of course it could be designed exactly the other way round. Consequently, the theorist is of course right as he states: "there is no difference between tube-watts and transistor-watts; watt as the unit for power is universally standardized". However, in just the same way the musician is correct in perceiving his or her tube amp as louder. It is not the unit of measurement that is different but the measurement process. A second difference is found in the resistance of the loudspeaker that is not constant, but frequency-dependent and complex. The magnitude of this complex resistance, the **impedance**, may easily reach 20 Ω or 30 Ω at certain frequencies although the loudspeaker is specified at 8 Ω. Not only the copper-resistance of the voice coil contributes to the impedance but also the inductance of the voice coil and the moving mechanic component as they are transformed into the electrical domain (Chapter 11). At the resonance frequency, the loudspeaker assumes high impedance, and the same happens at high frequencies.

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Fig. 10.9.4 shows the frequency responses of some guitar speaker boxes: the changes with frequency are most obvious. It is rather up to the manufacturer which impedance value he specifies for the respective box. There are indeed standards for this, however the musician and the manufacturer do no actually shake hands over a sales-deal based on specific DIN- or ANSI-norms. For the following consideration, we simply assume the loudspeaker impedance to be 8 Ω at *one* frequency, and 16 Ω at *another* frequency. If the amplifier has a transistor-typical "stiff" power supply and features an also transistor-typical strong negative feedback, the output voltage will be impressed i.e. almost independent of the load. With a 16-Ω-load, the amp will merely be able to feed half the power that it can generate in an 8-Ω-load. The situation is very different for a tube amplifier: operating it without a speaker could even cause flashover at the power tubes – the voltages that may occur are that high. The tube amp is not actually a true current source, but it does feature higher internal impedance compared to a transistor amp. This has consequences on the power delivery. For example: an amplifier with 8 Ω internal impedance feeds P_1 = 50 W into 8 Ω and P_2 = 44 W into 16 Ω. A (transistor-) amp with 0 Ω internal impedance would generate 50 W and 25 W, respectively. As the loudspeaker impedance increases, the power delivered by a transistor amp will decrease more strongly than for a tube amp. Again, the exact calculation is rather complicated because linear behavior (internal impedance) and non-linear behavior (limiting voltage) interact, and also because not a sine-tone but a guitar-signal drives the amp. Still, the statement remains: your typical tube amplifier will generate on average more power into a loudspeaker than a transistor amp having the same nominal power rating.

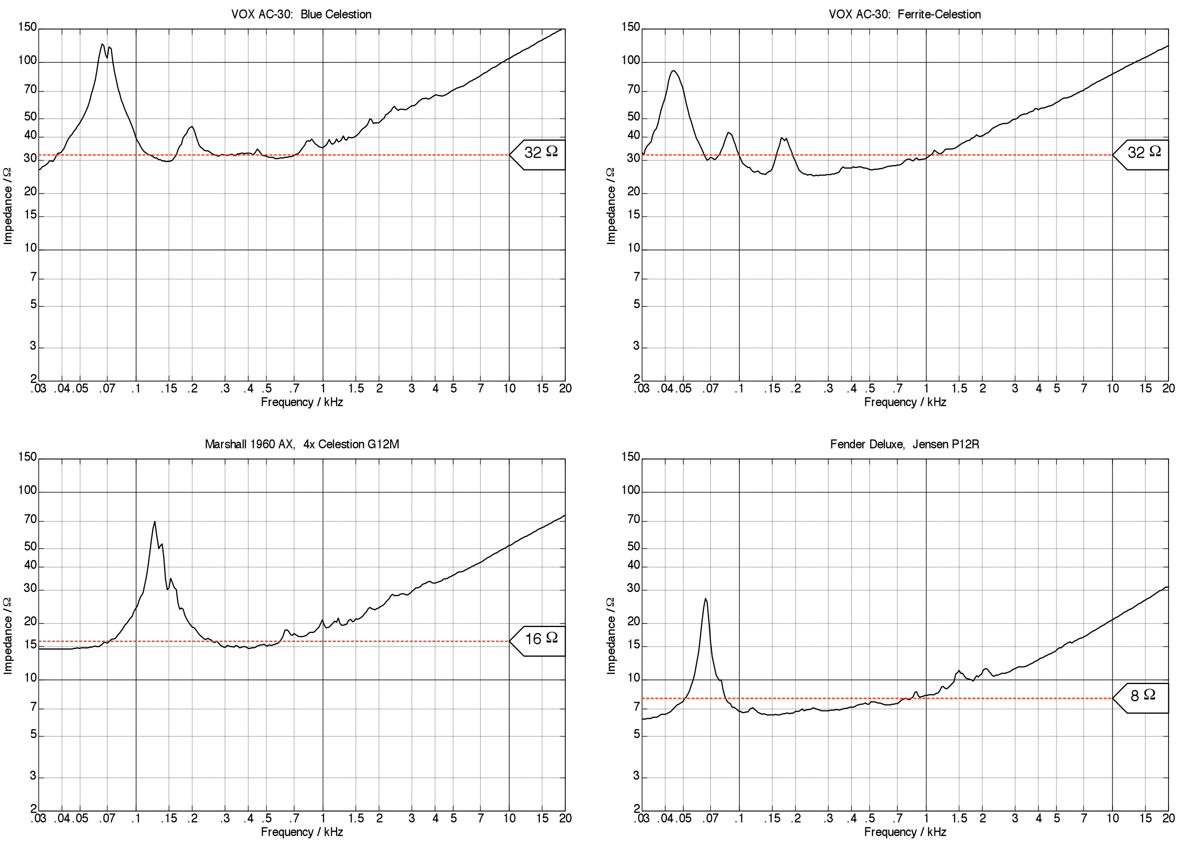

Fig. 10.9.4: Frequency responses (impedance) of typical guitar speakers; measured in a reflecting environment.

As an example we will look more closely at the frequency response of the speaker impedance of a Marshall 1960 AX speaker. It is specified at 16 Ω, its minimum impedance is 15 Ω.

Z reaches its maximum (70 Ω) at 130 Hz. A transistor amplifier rated for 16 Ω and fitted with a (ideally) stiff power supply will feed into 70 Ω merely 23% of the power that it could feed into 16 Ω. In reality, the power reduction will not be as pronounced because the supply voltage will sag less at increasing load-impedance – a reduction to "only" 30% is nevertheless quite drastic. A tube amplifier will behave quite differently: if it is specific for operation with 16-Ω-load, as well, we could expect 60% of the power at a 70-Ω-load, after all – double of what the transistor amp could generate. With a tube amp, the Marshall box will emphasize the frequency range around the resonance frequency, and it will reproduce the treble range more strongly. This tendency cannot be compensated for in the transistor amp by increasing the gain at high frequencies (e.g. by turning up the treble control) because that measure does not influence the maximum power delivery.

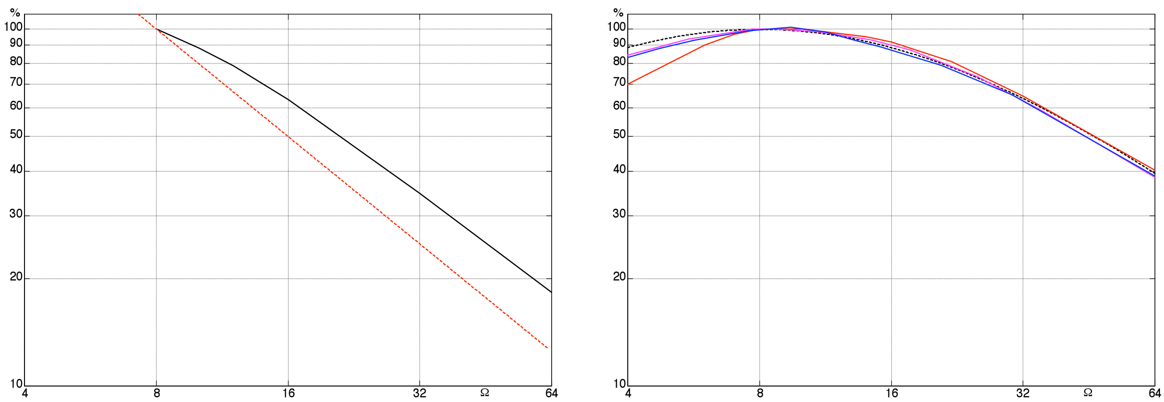

Fig. 10.9.5: Maximum available power dependent on the (ohmic) load resistance. Nominal impedance: 8 Ω. Left: typical transistor power-amp. Right: typical tube power-amp. Dashed: model-calculation.

In **Fig. 10.9.5**, the maximum available power is shown for a typical transistor power-amp and for three tube power-amps, respectively. "Maximum power" means total overdrive. The transistor amp is specified for 8 Ω; for lower loads the amp shuts down. The tube amps are also specified for 8 Ω but can deal with lower as well as with higher load impedances. For the transistor amp, a load-independent imprinted voltage was used as idealized **model**, while for the tube amps a constant internal **impedance** of R_i = 8 Ω was assumed. When discussing the internal impedance of a power amplifier, we need to distinguish between linear and non-linear behavior: during linear operation (no overdrive), the typical transistor amplifier features a very small internal impedance (e.g. 0,1 Ω or even less), while a tube power amp without any negative feedback (such as the VOX AC30) possesses e.g. 80 Ω (there are several variants). The AC30 therefore emphasizes already in its linear operational mode those frequency ranges where the loudspeaker features high impedance. In non-linear operation, the internal impedance can only be defined using special model laws; the dashed line in Fig. 10.9.5 was calculated for tube amplifiers and R_i = 8 Ω. Again, the frequencies of higher speaker impedance are emphasized although not as much.

The **VOX AD60-VT** realizes an interesting concept: this guitar amp uses a weak double triode (ECC83) as push-pull power amp and supplements the missing power via transistor-support. The peculiarity here is that the speaker impedance influences the power that the power amp is able to muster. The lone tube is not included as an alibi, as both power-measurement and listening tests prove (Fig. 10.9.6). What is not advertised as loudly, is that in the AC-30-power-amp, pentodes (EL84) do the work while in the AD-50 VT, triodes are on the job. They do, however, this job with very good success.

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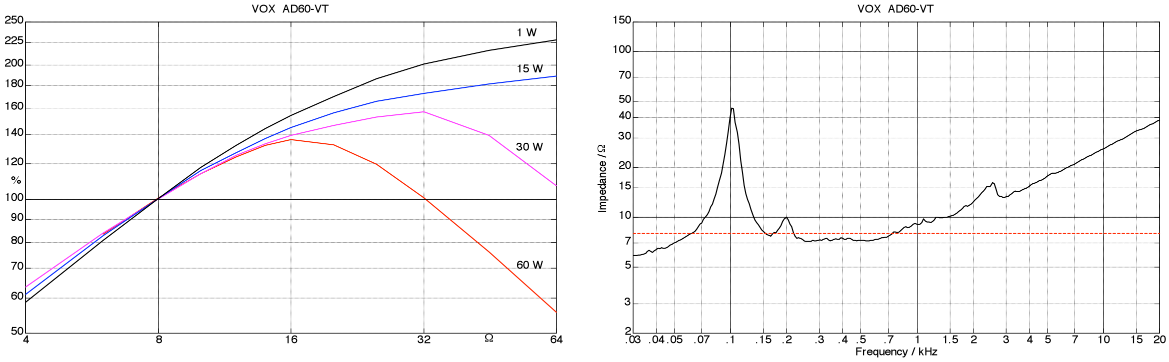

Fig. 10.9.6: VOX AD60-VT: standardized maximum power (left), frequency response of the impedance (right).

Fig. 10.9.6 depicts the maximum offered power dependent on the load resistor. The power-range selectable via a switch is the parameter. The power-characteristic is not really identical to that of a tube amp but the result is quite easy on the ears. Relative to the 8-Ω-reference, a boost can be seen and heard in the frequency ranges with higher speaker impedance – this boost is even stronger than that found with a "true" tube amp. In the 60-W-mode, the power maximum is at 16 Ω – this supports an operation with a (serially connected) second 8-Ω-speaker: more power is available although the treble boost effect is now getting a raw deal.

To summarize: both the impulse power (also termed peak power) and the power delivered in the higher-impedance frequency ranges of the speaker is higher for a typical tube amplifier than for a typical transistor amplifier – with are both rated at the same nominal power for the same nominal load resistance. A percentage value of the difference that would be generally valid can, however, not be given, since the individual circuit concepts are too different.

In closing we should quickly also visit the issue of **loudness** – which in the end is the main aspect of interest to the musician. It is well known that doubling the amplifier power will not always double the loudness. On the other hand, the rule taught in psychoacoustics that for doubling the loudness the 10-fold amplifier power is required, only holds for a 1-kHz-tone. The guitar generates a broadband sound that does not share much with a pure tone, and this naturally needs to be considered. However, of even more practical importance is the fact that the musician judges the loudness of his or her instrument based on how well it can (sonically) hold its own relative to other instruments. In this scenario, the absolute loudness is not as important as the so-called **partial masked loudness** [12]. For example, we may think of a keyboard player sounding a loud chord, and of a guitar player remaining unheard[1] although his amp generates 10 W into the loudspeaker. The latter is not broken at all, but the sound it radiates is fully masked by the sound of the keyboard. As the power of the guitar is increased (e.g. to 20 W), the guitar becomes audible. However, as long as the keyboard is sounded, the loudness of the guitar remains a partial masked loudness and the guitar will be perceived softer compared the loudness it would have when played on its own. For the increase of the partial masked loudness the simple 10-dB-per-doubling-of-loudness law does not hold; a smaller dB-value is valid, e.g. merely 3-dB per loudness doubling. That way, relatively small power-differences gain a bit more significance than basic psycho-acoustical know-how would acknowledge. We shouldn't overdo it, though. The difference between a 50-W-amp and a 55-W-amp remains insignificant. The exact location of the perception-threshold can only be established for each case individually because the masking effects are dependent on the temporal and spectral structure of the involved sounds.

[1] *Translator's comment: the guitar not loud enough - as if that ever happened! Not a realistic example, it seems. Maybe the other way 'round ..... the Leslie for the Hammond won't ever match the Marshall stack, anyway ...*

