Sound-generating Parameters of Starting Electric Railbound Vehicles and their Influence on Sound Quality

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1. Introduction

In recent years, research activities and sound-abatement measures in the field of electric railbound vehicles (e.g. trams, subways or light-rail vehicles) have been mostly concentrated on rolling noise. On the other hand, some additional noise components often play an important role especially during the starting phase of modern vehicles. Among them, one can point out the motor in connection with the traction converter apart from other sources such as the gear coupling. The acoustic optimisation potential of this kind of noise, called "traction noise", is rather unknown.

Therefore, a study concerning sound sources, relevant psycho-acoustic quantities and optimisation measures of traction noise is carried out. In this contribution, a short overview of the sound-generating parameters is presented, including a first estimation of their influence on psychoacoustic quantities.

2. Classification of traction-noise sources

Although traction noise can sound quite differently, in almost every case it consists of tonal components. The main interest in this paper is to explain their frequencies rather than their amplitudes.

Figure 1 shows a frequency-vs.-time diagram measured during an acceleration in the passenger cabin of a typical vehicle. Each of the visible tones is caused by traction components, and it can be seen that the sound character changes within the time history.

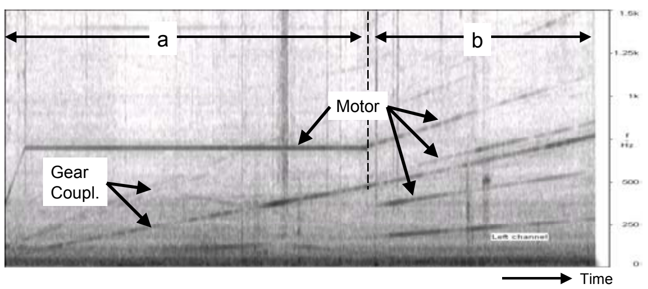

Figure 1: FFT vs. time measured inside a typical vehicle with GTO converter

2.1 Traction motor

One main noise source is the motor itself. It acts like a shaker, since electrical energy is transformed into forces exciting the stator or bogie structure. Time-varying forces in the airgap can act in both radial and tangential direction. The radial (Maxwell) stress σ along the perimeter φ results from two induction waves b_1 and b_2 [1]

$$\sigma(\varphi,t) = b_1(\varphi,t) \cdot b_2(\varphi,t) / 2\mu_0, \qquad (1)$$

whereas the tangential oscillating torque T ("torque ripple") results from a current sheet wave a and an induction wave b [2]

$$T(t) \sim \int_0^{2\pi} a(\varphi,t) \cdot b(\varphi,t)\, d\varphi \qquad (2)$$

Note that oscillating torques should not be mixed up with the (wanted) constant torque. Both quantities, a and b, usually have the same tonal components since they are both based on the current $i(t)$.

In order to classify traction motors, it can be observed that older vehicle drives with DC motors are hardly audible. This is evident because a current signal at zero frequency will not produce audible tones. From the acoustic point of view, modern traction drives are therefore much more critical. Induction machines (asynchronous machines), used in railbound-vehicle drives for about 25 years, must be fed with three-phase current signals which are varying in amplitude and frequency. These signals are provided by a traction converter. It is impossible to supply the machine with a perfect sinusoidal sweep signal, since converters are made of valves switching a signal on and off. It is evident that this yields harmonics in the current and corresponding force spectra.

The main effect within the signal transmission is that harmonics of the current signal are transformed to other frequencies in the stress or torque signal. In the case of railbound vehicles, excitation type (2) is usually more prominent than (1) due to low eigenfrequencies of the bogie structure. In this case, two waves (a_i and b_j) with frequencies ω_i and ω_j yield $\omega = |\omega_i - \omega_j|$ in the torque signal [2]. After the subsequent signal-transmitting elements (i.e. structure-borne sound transmission, radiation, room acoustics), these excitation frequencies are still clearly audible, whereby the signal is affected with resonances and filter functions [3].

2.2 Traction converter

The traction converter itself does not radiate much noise, but the critical current harmonics are generated here. A classification of different converter types which are used for railbound-vehicle drives is given in the following Table:

valve type	used since	max. frequency	typical circuit type	typical switching type
Thyristor	~1980	~200 Hz	current-source	synchronous
GTO	~1990	~600 Hz	voltage-source	asynchronous[1)] synchronous[2)]
IGBT	~1995	~2 kHz	voltage-source	asynchronous

[1)] lower speeds, [2)] higher speeds

A complete explanation of this table would be too extensive, so that only some essential statements can be outlined here:

The oldest valve type, the thyristor, can only be switched on but not off actively. The appropriate implementation is a current-source circuit in combination with a fixed signal called "phase-sequence", sketched in Figure 2.

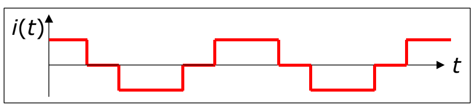

Figure 2: Idealised phase-sequence current signal for one stator winding

By contrast, the Gate-Turn-Off Thyristor (GTO) and the Insulated Gate Bipolar Transistor (IGBT) provide both switching on and off. They allow more variable signals, and both valves are usually implemented in a voltage-source circuit. The IGBT is the most modern device with the highest maximum switching frequency.

For more information about these devices see [4][5][6]. Sections 3 and 4 will focus on acoustical effects due to these techniques.

2.3 Gear coupling

Tonal components from the gear couplings are audible in almost every railbound vehicle. The fundamental frequency is connected to the small gear teeth number Z_{small} by $\omega_{audible} = Z_{small} \cdot \omega_{motor}$. Many vehicles have two-section couplings, whereby a second tone is obtained by $\omega_{audible,2} = (Z_{small,1} / Z_{big,1}) \cdot Z_{small,2} \cdot \omega_{motor}$. Note that ω_{motor} is not the electric motor frequency ω_0, but $\omega_0 = \omega_{motor} \cdot p$ with p = motor pole-pair number.

3. Effects due to synchronous switching

The notion "synchronous" indicates that the periodicity of the current signal is adapted to the electric motor frequency. During an acceleration, tones are therefore audible as sweeps.

3.1 Current-source converter

A phase-sequence current signal (see Fig. 2) contains the following harmonics: $1\omega_0$, $-5\omega_0$, $7\omega_0$, $-11\omega_0$ etc. [5] whereby negative signs indicate a reversed wave propagation along the perimeter. The audible frequencies $|\omega_i - \omega_j|$ are mainly $6\omega_0$, $12\omega_0$, $18\omega_0$ etc. In addition to a high tonality, the sharp edges in the signals yield high-order harmonics and hence a high sharpness.

3.2 Voltage-source converter

At higher speeds, voltage-source converters with GTOs are also operated with synchronous switching, but with more variable pulse patterns, see e.g. Figure 3.

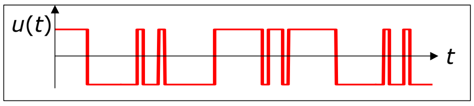

Figure 3: Typical voltage pulse pattern (at inverter terminal [7])

Audible frequencies are again $n(6\omega_0)$, n=1,2,3.. In comparison with Sec. 3.1, the main difference is that sharp edges are only obtained in the voltage signal, so that a "smoother" current $i(t) \sim \int u(t)\,dt$ yields a lower sharpness. On the other hand, pulse-pattern optimisation [8] cannot completely avoid amplifications for some single harmonics, increasing their tonality. In addition, many vehicles are operated with pulse patterns changing at discrete speeds [8][9].

In general, one important characteristic of synchronous switching is that harmonics $n(6p \cdot \omega_{motor})$ form a musical interval with the gear frequencies $n(Z_{small} \cdot \omega_{motor})$ (see Sec. 2.3 and Fig. 1) so that it is interesting to study consonance effects.

4. Effects due to asynchronous switching

4.1 PWM with constant carrier frequency

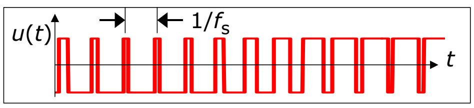

Figure 4: Typical PWM voltage signal (at inverter terminal [7])

Pulse-width modulation (PWM [7], see Figure 4) can yield a quite sinusoidal current signal if the switching (=carrier) frequency f_S is much higher than the motor frequency - this is the reason why drives with GTOs use PWM only at lower speeds, see phase a in Fig. 1. Instead of synchronous harmonics like in Sec. 3, audible frequencies are mainly $2f_S$ and its harmonics $2nf_S$ apart from sidebands. It is evident that the carrier frequency produces a high tonality, whereby typical frequencies are about 1 kHz for drives with GTOs and about 3-5 kHz for drives with IGBTs.

4.2 PWM with variable carrier frequency

The carrier frequency f_S does not need to be constant. Therefore, several frequency-variation techniques have been developed in order to improve dynamic, economic, or acoustic performance of vehicle drives. They are all currently used in railbound vehicles:

a) switching from a lower to a higher f_S when vehicle starts (see Fig. 1, at the beginning of phase a)
b) periodic modulation of f_S (PCFM) [10]
c) random modulation of f_S (RCFM) [11]
d) direct torque control (DTC) [9][12]

Each of this techniques is clearly audible, yielding the following tendencies in comparison with constant f_S:

technique	expected psychoacoustic effect
a) increasing f_S	temporal activity when f_S increases
b) PCFM	slightly lowered tonality, high roughness
c) RCFM	significantly lowered tonality
d) DTC	high temporal activity

5. Conclusion

In this contribution, an overview of the sound-generating process of traction noise was presented, and several parameters with a possible influence on sound quality were outlined. Since it is impossible to explain each of the techniques in detail on two pages, several helpful references are proposed. The paper should be understood to give basic knowledge for an accompanying paper about perception of traction noise [13].

6. References

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