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SOUND DESIGN FOR ELECTRIC CARS: WHAT CAN WE LEARN FROM COMBUSTION ENGINES?

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Abstract: *While the USA and Japan have already regulated it some years ago, the EU has just only decided: Electric cars will not be allowed to drive noiseless anymore and they will have to generate exterior sound at low speeds to warn other traffic participants, especially pedestrians. It seems also reasonable to inform the driver about the driving state (speed, engine load) by generated interior sound. But how are electric cars supposed to sound: exactly like a car with a conventional combustion engine, like a space ship, or like bird's twittering? What is sure is that all traffic participants inside and outside the car are familiar with the sounds of combustion engines. It is thus obvious to employ these familiar sound characteristics for electric cars, too. This contribution presents an analysis method for sound of combustion engines that results in a parametric representation, which in turn allows for a real-time synthesis of the engine sound. Based on the analysis results, typical characteristics of different combustion engines are discussed from a musical perspective.*

Keywords: sound design, electric cars, interior and exterior sound

1. INTRODUCTION

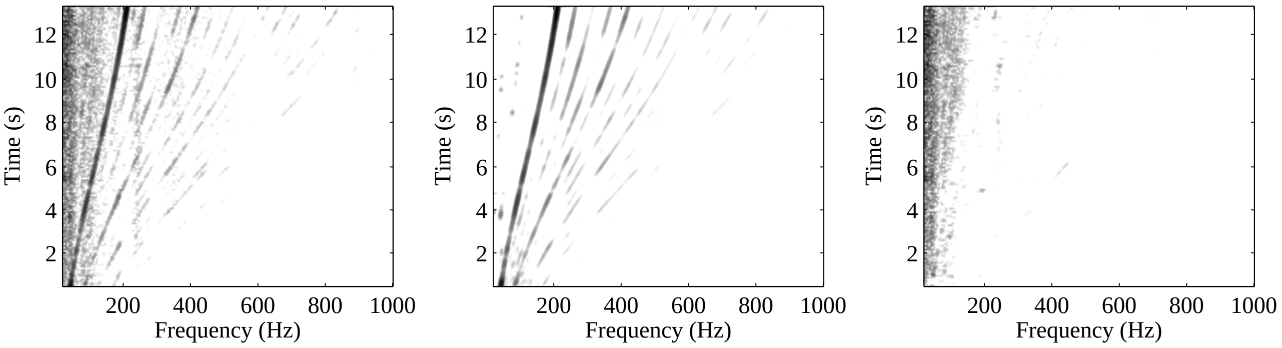
Electric cars do not generate as much sound as vehicles with conventional combustion engines and thus set the stage for quieter cities. However, the low exterior sound level yields potential risks for other traffic participants, e.g. pedestrians and cyclists, especially at vehicle speeds below 30 km/h. The detection distance in pass-by tests at constant speeds was found to be much smaller for such cars [1]. It is especially dangerous, when the car drives behind a car with internal combustion engine. That is why the U.S. Department of Transportation National Highway Traffic Safety Administration (NHTSA) regulated the minimum sound power requirements for hybrid and electric cars in dependence of different conditions and speeds [2] and proposes Active Sound Generation (ASG).

A lot of research started about how the characteristics of such sounds should be. Although [3] shows that frequency components below 1600 Hz are completely sufficient for detecting the sound of a vehicle from ambient noise at a safe distance, [4] proposes two-band sounds with an additional third-octave band between 2 kHz and 5 kHz. Japan [1] prohibits sounds that could be confused with bird's twittering or sirens. Moreover, the commencing motion is an important topic: Its detectability can be increased by using a distinct start-up sound and avoiding sound at idle state [5].

Although most customers prefer a quiet car, loudness adaptation according to driving situation, e.g. load-dependency, is an important factor for the acceptance of interior sound [6]. Studies about interior car sounds from combustion engines and electric engines (without ASG) describe the latter as barely sporty [7]. Sportiness in electric cars appears to require ASG. Additionally, the perceived acceleration can be increased by pitch shifting [8].

There seems to be a wide range of possibilities for sound design that is consistent with legal regulations. Although it is stated in [1] that the possibilities for sound design at the manufacturer should be limited, we think that manufacturer and customers of premium and sports cars will not give up manufacturer-individual characteristics of both interior and exterior sound. Therefore, this paper presents possibilities to learn from the traditional sound of combustion engines and to transform these characteristics into new sounds for electric cars.

The paper is arranged as follows: Section 2 introduces a parametric model for analysis and re-synthesis of recorded engine sounds. The subsequent section presents the theoretical harmonic structure of combustion engines in dependence of the number of cylinders. Moreover, it exemplarily examines the harmonic structure of real engine recordings. Section 4 discusses other characteristic sound parameters. Finally, the paper is summarized and concluded.



(a) original recording (b) real-time synthesis (c) difference

Fig. 1. Spectrogram (40dB dynamic range) of a full-load run-up of a 4-cylinder gasoline engine (recorded in a car interior), its parametric real-time synthesis, and the difference between original recording and synthesis.

2. ANALYSIS AND RE-SYNTHESIS OF COMBUSTION ENGINE SOUNDS

This section presents an analysis and re-synthesis system that allows for complete recreation of combustion engine sounds. The whole system is based on engine orders (multiples of the engine speed = revolutions of the crank shaft in rpm). For each engine order, it employs parameter sets consisting on rpm-dependent amplitude, amplitude modulation, and phase modulation. A full description of an engine sound consists of three parameter sets: full-load, proportional load, and recuperation. Depending of the engine load, the system interpolates between the three parameter sets.

The parametric approach is a prerequisite for fast responding ASG. Real-time parameter changes are controlled manually during the sound design process or via standardized OBD or CAN-Bus protocols in the final application. The adaptation to further future protocols is easily possible.

2.1. Analysis

The analysis delivers a full parameter set of amplitude, amplitude modulation, and phase modulation for each engine order at 128 equally spaced sampling points of the engine speed. The analysis is performed for each of the three above-mentioned driving states individually and its duration is similar to the duration of the analyzed recording. The microphone recordings are analyzed using the second generation Vold-Kalman filter [9, 10]. These filters are designed to track signals of a known structure among signals of a different structure. In our case, we know that the engine sound comprises harmonics of the engine speed, i.e. engine orders. A prerequisite for successful order tracking is the precise knowledge of the reference engine speed at each point in time. Therefore, the corresponding engine speed has been captured synchronously with the microphone recordings. The filtering process yields a time-domain bandpass signal for each tracked order individually. For each bandpass signal, the amplitude values are obtained by calculating the envelope. Moreover, the time-domain signals allow for the determination of amplitude modulation and phase modulation. The analysis employs a resolution of a quarter order, however only the half-order components are maintained in the parameter sets. The additional information of the quarter-order components is used to reduce dominant disturbing noise at low frequencies that is caused by other sound sources, e.g. tread noise. At each rpm sampling point, the final parameter sets include only those half orders which contain significantly more energy than the neighboring quarter-order components.

2.2. Parametric Real-Time Synthesis

The whole synthesis is implemented in the visual programming language Pure Data[1] (pd). As pd is open-source, it can be compiled for arbitrary computer platforms providing fast adaptation to customer needs, such as low-power computers. Exemplarily, we have successfully tested the synthesizer on a Raspberry Pi.

The synthesizer provides 128 oscillators simultaneously and is thus able to synthesize up to the 32$^{\text{nd}}$ engine order in steps of quarter orders. Each of the oscillators has exactly the same structure and is parametrized by frequency, gain, amplitude modulation, and phase modulation. In order to save computational load for the application on low-power computers, each oscillator can be (de)activated individually. The full description of an engine sound including the parameter sets for the three driving states is stored in a matrix with approx. 200 K elements.

Exemplarily, Fig. 1 shows the spectrogram of a full-load run-up recorded in the car interior on the dynamometer at AVL. The recording has been analyzed and re-synthesized using the system described above. The synthesis employs only full and half engine orders. The difference between the original recording and its re-synthesis is limited to the low-frequency rolling noise of the tires on the dynamometer. As this difference includes only the actually unwanted part of the recording, the clear synthesis of the engine sound succeeded.

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[1] freely available at `http://www.puredata.info`

3. INFLUENCE OF NUMBER OF CYLINDERS ON HARMONIC STRUCTURE OF ENGINE SOUNDS

The number of cylinders defines the basic harmonic structure of the engine sound. This section discusses the physical background, as well as resulting theoretical harmonics and practical measurements.

3.1. Physical Background

Nowadays, cars are typically driven by four-stroke engines. In these engines, the piston of each cylinder completes four strokes within a single thermodynamic cycle comprising of intake, compression, power, and exhaust. The (self-)ignition occurs at the beginning of the third stroke and causes the combustion of the compressed fuel-air mixture. This event generates most of the engine sound and its frequency determines the dominant frequency of this sound, the so-called firing frequency.

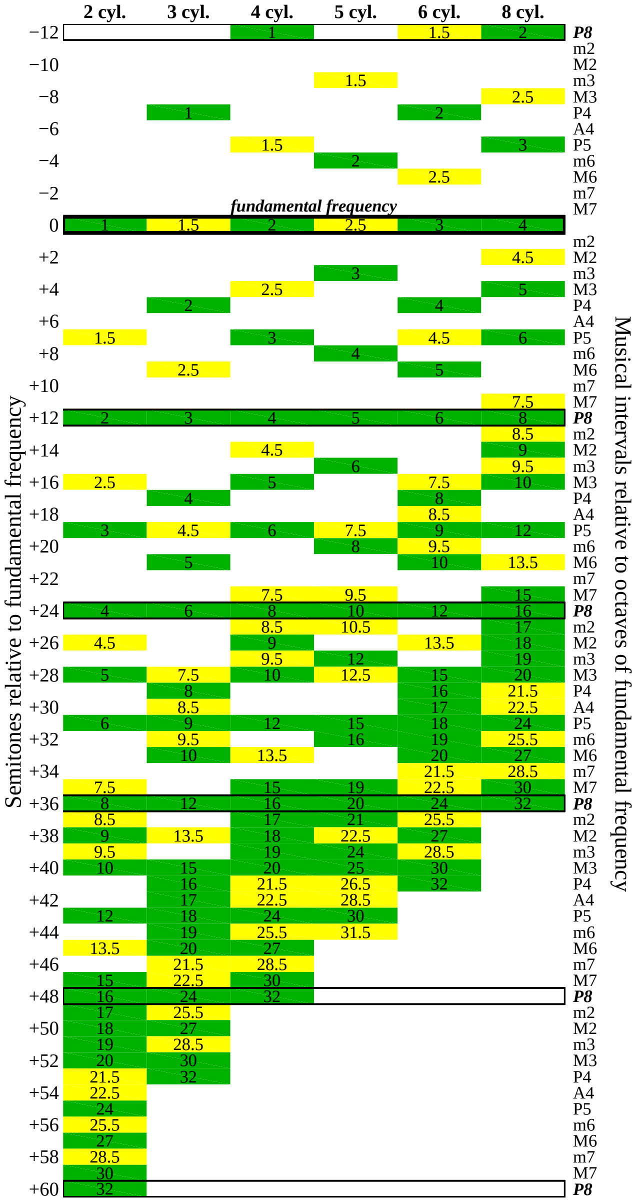
During a complete cycle of a four-stroke engine, the crank shaft turns two times. Thus, in case of an engine with only one cylinder, the engine speed is twice the firing frequency, resulting in a dominant engine order of 0.5. In engines with more cylinders, the firing of the cylinders occurs interleaved. In case of a 4-cylinder engine, the firing frequency is twice the engine speed. Thus, the number of cylinders n_{cyl} determines the dominant engine order n_{dom} of the engine sound

$$n_{dom} = \frac{n_{cyl}}{2}. \tag{1}$$

In musical terms, i.e. perceived pitch, the dominant engine order can be interpreted as the fundamental frequency.

3.2. Theoretical Harmonic Structure

Based on the above-mentioned physical background and expanding the investigation in [11], Fig. 2 shows the harmonic structure of engines with 2, 3, 4, 5, 6, and 8 cylinders. It only considers half and full engine orders that deviate less than 1% from semitones on a well-tempered scale. The fundamental frequency of the engine obviously increases with the number of cylinders. Similarly, the harmonic structure relative to the fundamental frequency becomes denser. Comparing a 2-cylinder and a 4-cylinder engine within their first octave, the larger engine creates an additional major third. Thus, the 4-cylinder engine evokes the impression of a richer major chord.



fundamental frequency

Semitones relative to fundamental frequency	2 cyl.	3 cyl.	4 cyl.	5 cyl.	6 cyl.	8 cyl.	Musical intervals relative to octaves of fundamental frequency
−12			1		1.5	2	***P8***
							m2
−10							M2
				1.5			m3
−8						2.5	M3
		1			2		P4
−6							A4
			1.5			3	P5
−4				2			m6
					2.5		M6
−2							m7
							M7
0	1	1.5	2	2.5	3	4	
							m2
+2						4.5	M2
				3			m3
+4			2.5			5	M3
		2			4		P4
+6							A4
	1.5		3		4.5	6	P5
+8				4			m6
		2.5			5		M6
+10							m7
						7.5	M7
+12	2	3	4	5	6	8	***P8***
						8.5	m2
+14			4.5			9	M2
				6		9.5	m3
+16	2.5		5		7.5	10	M3
		4			8		P4
+18					8.5		A4
	3	4.5	6	7.5	9	12	P5
+20				8	9.5		m6
		5			10	13.5	M6
+22							m7
			7.5	9.5		15	M7
+24	4	6	8	10	12	16	***P8***
			8.5	10.5		17	m2
+26	4.5		9		13.5	18	M2
			9.5	12		19	m3
+28	5	7.5	10	12.5	15	20	M3
		8			16	21.5	P4
+30		8.5			17	22.5	A4
	6	9	12	15	18	24	P5
+32		9.5		16	19	25.5	m6
		10	13.5		20	27	M6
+34					21.5	28.5	m7
	7.5		15	19	22.5	30	M7
+36	8	12	16	20	24	32	***P8***
	8.5		17	21	25.5		m2
+38	9	13.5	18	22.5	27		M2
	9.5		19	24	28.5		m3
+40	10	15	20	25	30		M3
		16	21.5	26.5	32		P4
+42		17	22.5	28.5			A4
	12	18	24	30			P5
+44		19	25.5	31.5			m6
	13.5	20	27				M6
+46		21.5	28.5				m7
	15	22.5	30				M7
+48	16	24	32				***P8***
	17	25.5					m2
+50	18	27					M2
	19	28.5					m3
+52	20	30					M3
	21.5	32					P4
+54	22.5						A4
	24						P5
+56	25.5						m6
	27						M6
+58	28.5						m7
	30						M7
+60	32						***P8***

Fig. 2. Half (yellow) and full (green) engine orders that fit musical intervals (m=minor, M=Major, P=perfect, A=augmented) with a deviation of less than 1% (17 cents) for different numbers of cylinders.

3.3. Practical Measurements

An exemplary evaluation of real engine sounds is depicted in Fig. 3. The evaluation is based on the above-mentioned analysis and compares the relative amount of energy that contributes to the impression of a major chord for engines with different number of cylinders. This energy comprises the energies of the major thirds and perfect fifths in all octaves of the fundamental frequency. It is obvious that the relative amount of major components of the 8-cylinder engine is larger than the 4-cylinder engine. The smallest engine exhibits the smallest amount of major components.

This is caused by several reasons: In general, the energy transfer form the engine to the car interior has a low-pass characteristic. Moreover, the emitted energy is focused on integer engine orders close to the fundamental frequency and below. The 8-cylinder yields even several subharmonics that support the major components, cf. Fig. 2.

Adding specific engine orders can also be applied for ASG to improve the interior sound of cars with down-sized combustion engines [12, 13].

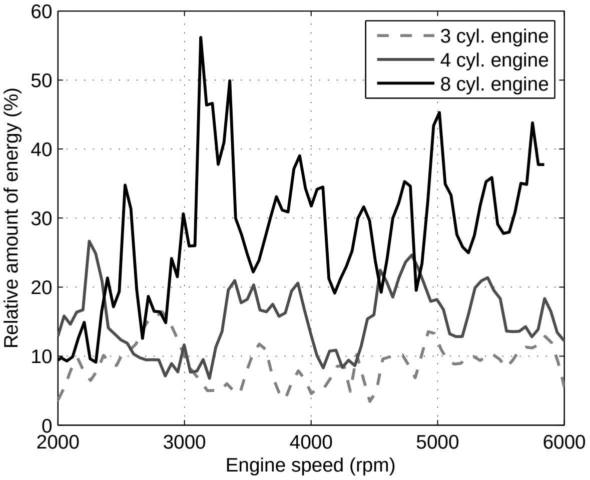


Fig. 3. Major sound character (energy in major 3rds and perfect 5ths related to all analyzed engine orders from 0.5 to 32) in dependence of engine speed for different number of cylinders.

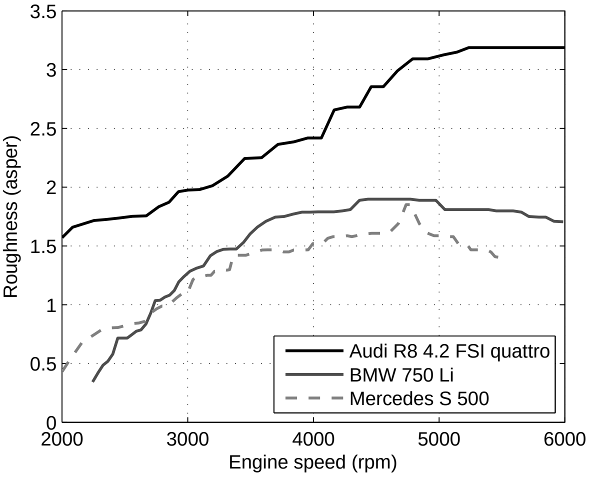


Fig. 4. Roughness of interior noise during full-load run-ups on different 8-cylinder gasoline engines in dependence of engine speed.

4. OTHER PARAMETERS

The previous section investigated the harmonic structure in dependence of the number of cylinders. In addition, the relative strength of the engine orders depends on auxiliary components, such as mufflers, and the construction of the engine, e.g. in-line, V, boxer. These properties create the different sounds of engines with the same number of cylinders. Besides the harmonic structure, other sound parameters play an important role, such as rpm-dependent loudness, formants/resonances, or temporal variation.

Roughness is one of the main parameters for temporal variation, and it enriches the perceived timbre and results in more powerful sounds. Fig. 4 shows the rpm-dependent roughness for three different 8-cylinder gasoline engines. As expected, the two limousines (BMW, Mercedes) have a similar characteristic, whereas the sports car (Audi) exhibits more roughness at all engine speeds. This tendency is most prominent at low and high rpm.

In combustion engines, roughness is typically created by close neighboring engine orders that cause fast amplitude fluctuations. In order to provide sportiness to electric cars, the roughness can directly be applied to the sound design by introducing amplitude modulation.

5. CONCLUSION AND OUTLOOK

Based on the existing regulations, it is obvious that electric cars must be equipped with ASG for exterior noise at low driving speed. Still there is a wide range of possibilities for sound design that is consistent with these regulations and goes beyond mere vehicle alert signals. We suggest the application of familiar characteristics known from combustions engines in order to maintain the tradition of manufacturer-individual and utilization-fitted sounds.

This does not necessarily mean to simulate the existing sounds of combustion engines, it rather provides the possibility to gradually draw on already established experiences. For example, the harmonic structure of a Porsche 6-cylinder boxer engine is a unique sound character that could be transferred to future Porsche electric cars.

Additionally, we suggest ASG to design and enhance the interior noise in order to assist drivability and further improve experience of electric cars. The design of interior and exterior noise can both benefit from the experience and knowledge of combustion engine sound. The presented analysis approach provides the means for retrieval and transfer of relevant sound characteristics to electric cars.

Gradually abstractions can be achieved using different synthesis approaches: The presented order-based sinusoidal approach provides an accurate re-synthesis. Replacing these oscillators by narrow-band filters allows for the application of arbitrary sound textures as base material. These sound textures can be created by condensing [14] audio material, such as natural ambient sounds, instruments, or even entire musical pieces. Further effects, such as pitch shifting and amplitude modulation, can be added to evoke specific impressions, e.g. sportiness and acceleration.

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REFERENCES

[1] K.-P. Glaeser, T. Marx, and T. Marx: **Testing the sound detection of electric vehicles by blind or visually impaired persons**, in *Forum Acusticum*, 2014

[2] U.S. Department Of Transportation National Highway Traffic Safety Administration: ***Minimum sound requirements for hybrid and electric vehicles***, NHTSA-2011-0100, 2013

[3] M. E. Altinsoy, J. Landgraf, M. Lachmann, M. Esser, and D. Volkenborn: **Investigations on the detectability of synthesized electric vehicle sounds - vehicle operation: Approaching at 10 km/h**, in *Forum Acusticum*, 2014

[4] I. Sakamoto, M. Sekine, K. Morita, and H. Houzu: **Research for standardization of measures against quiet HV/EV in Japan**, in *Forum Acusticum*, 2014

[5] M. E. Altinsoy, J. Landgraf, M. Esser, and D. Volkenborn: **Electric vehicle alert sound design - comparison of commencing motion sound and sound at idle**, in *Forum Acusticum*, 2014

[6] J. Kerkmann, B. Schulte-Fortkamp, A. Fiebig, and K. Genuit: **Acceptance of synthetic driving noises in electric vehicles**, in *Forum Acusticum*, 2014

[7] H. Sukowski, R. Kühler, S. van de Par, and R. Weber: **Development and application of a new adjective list for the assessment of interior sounds of electric vehicles**, in *Forum Acusticum*, 2014

[8] K. Yamauchi and J. Feng: **Effect of frequency shifting of additional sound for electric vehicles on acceleration impression**, in *Forum Acusticum*, 2014

[9] H. Vold and J. Leuridan: **High resolution order tracking at extreme slew rates, using Kalman tracking filters**, SAE Technical Paper, Tech. Rep., 1993

[10] J. Tuma: **Setting the passband width in the Vold-Kalman order tracking filter**, in *12th International Congress on Sound and Vibration*, 2005

[11] N. Alt and S. Jochum: **Sound-Design unter den Aspekten der Harmonielehre der Musik**, *MTZ-Motortechnische Zeitschrift*, 64(1), 2003, 48–56

[12] A. Sontacchi, M. Frank, F. Zotter, C. Kranzler, and S. Brandl: **Sound Optimization for Downsized Engines**, SAE Technical Paper, 2014

[13] R. Schirmacher, R. Kunkel, and M. Burghardt: **Active Noise Control for the 4.0 TFSI with Cylinder on Demand Technology in Audi's S-Series**, SAE Technical Paper, 2012

[14] R. Höldrich: ***Method for processing audio data into a condensed version***, US Patent 71 576 607, 2008