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RESEARCH ARTICLE

Effect of Material Changes on the Total Harmonic Distortions Caused by Aluminum Electrolytic Capacitors

RENÉ KALBITZ
Würth Elektronik eiSos GmbH, 74638 Waldenburg, Germany
Capacitors and Resistors Product Unit, Competence Center Berlin Branch, 12489 Berlin, Germany
e-mail: Rene.Kalbitz@we-online.de

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ABSTRACT This paper describes a comparative study of the total harmonic distortion (THD) caused by commercial electrolytic capacitors. The study includes selected capacitors with a capacitance of 470 μF that are commercially available from eiSos Würth Elektronik, as well as custom-made capacitors that are manufactured at the production site. For the custom-made samples, the water content of the electrolyte, as well as the paper density, was systematically varied. The discussion of audibility of distortion is based on human sound perception. The results are compared with model calculations to check the plausibility of the measured harmonic distortions. This study concludes that capacitors do not introduce significant distortions at fundamental frequencies when transmitting signals. Modifications of the electrolyte or the separator paper practically do not influence the THD.

INDEX TERMS Acoustic effect, aluminum electrolytic capacitors, distortions, human hearing, psychoacoustic, total harmonic distortions, THD.

I. INTRODUCTION

There is an ongoing debate in the audio engineering community about the audio quality of amplifiers and the audibility of signal distortion [1], [2] [3], [4], [5], [6]. Capacitors are used to separate dc signals, i.e. bias voltages of audio signals, from ac signals in amplifier circuits [1]. They are also used to adjust the frequency response so that the amplified signal can be sent to two or more speaker drivers, each covering different frequency ranges [2]. Moreover, capacitors are utilized to filter interference or act as a buffer for large power surges.

Apparently, capacitors are suspected of being the cause or at least one of the causes of high-frequency distortions that affect the hearing impression [1], [2]. It appears that some developers use only certain brands or types of capacitors based on their subjectively experienced sound quality. It is suspected that the components used in these capacitors might influence the signal transduction and, thus, the sound quality. Apart from web pages, there is not much scientific literature dealing with distortion caused by commercial capacitors in variations of their components, such as separating papers and electrolytes.

Anderson has published a detailed survey on commercially available capacitors using an audio circuit; however, he has not had the opportunity to make any statements about the components of the capacitors or to discuss the results in reference to psychoacoustics [1]. Anderson's work mainly focuses on thoroughly interpreting the total harmonic distortions (THD) for different gains. He concluded that differences in capacitor-related distortions between a variety of electrolytic capacitors are negligible.

Duncan et al. published a study on the influence of mechanical resonances in film capacitors on audio delivery using subjective listening tests [2]. He concluded that mechanical resonances within the film capacitor, used in a loudspeaker crossover, may indeed influence sound.

This work aims to complement the discourse on capacitors and their influence on distortion by studying the influence of different capacitor constituents on THD. Discussing the audibility of distortion includes measuring electrical properties and interpreting them in terms of how the human auditory system may perceive them. This article reports a study of THD

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caused by electrolytic capacitors, as produced by Würth Elektronik eiSos, and purpose-built items. Although this study does not contain any psychoacoustic experiments, it attempts to interpret the results based on the literature.

In order to find parameters that influence the THD, capacitors with different separator papers and electrolyte compositions were examined. These sample capacitors were assembled at a production site under near-mass production conditions and analyzed in Würth Elektronik's electrical laboratory in Berlin.

To enable the reader to interpret the results, the article first introduces the field of human hearing and psychoacoustics before turning to the study of harmonic distortion in capacitors. In addition, results from model calculations are presented in order to check the measurement results for plausibility.

II. REVIEW OF HUMAN HEARING

This section introduces the topic of human sound perception and how it can be quantified. It defines terms such as loudness and hearing threshold as well as summarizes the discussion about predicting the audibility of distortions.

The human ear can perceive sound waves in the frequency range between about 20 Hz (lower limit) and 16 kHz (upper limit) [7]. Therefore, a sound in this range (audible window) is called audible sound. Sound below 20 Hz is called infrasound and sound above 16 kHz is referred to as ultrasound.

A graphical representation of the auditory sensation is achieved, if the sound pressure level is plotted over the audible frequencies, as in Fig. 1 [8]. The curves drawn in the graph are called isophones and represent curves of equal loudness, measured in the unit phon. Isophones relate the sound pressure, measured in dB, to the loudness level. A sound with a level of 50 phon is perceived as just as loud as a 1 kHz tone with a sound pressure level of 50 dB.

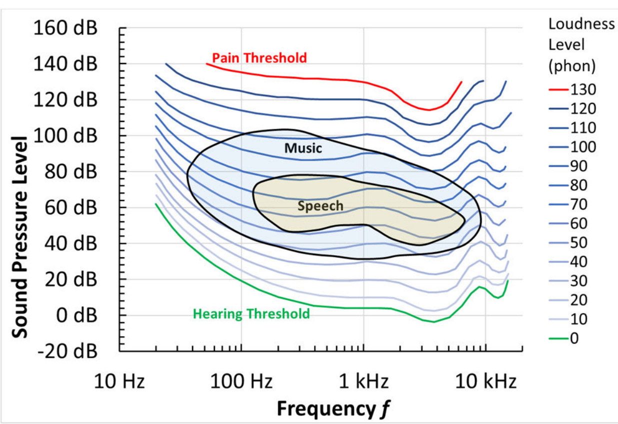

FIGURE 1. Depiction of equal loudness curves and auditory sensation areas [7], [8].

Another term sometimes synonymically used for loudness but also for the signal amplitude is volume. The volume is not so well defined but is mostly found on technical equipment and used to describe the amplitude of a signal. Practically, the listener adjusts the volume at the interface of equipment to adjust the loudness. Although this term is not used in this work, it is used in some literature and, thus, introduced for the sake of completeness.

Equal loudness level means that regardless of the frequency, each tone in the course of a curve is perceived as equally loud. The loudness is, thus, a perception value (psychoacoustic), in contrast to the sound pressure, and represents a stimulus value [9], [10], [11].

In this plot, the lowest graph indicates the threshold of hearing. This threshold applies to measurements with sine tones in a free sound field binaural hearing. The sound pressure level is related to the sound pressure of 20 μP. With this definition, the sound pressure level at the hearing threshold at 1 kHz is 4 dB. The area for speech is much smaller than the range of hearing. Even music encompasses only one sub-area of the entire hearing range.

The hearing threshold is strongly frequency-dependent. In the range between 2 kHz and 5 kHz, the auditory sensitivity is greatest. In this range, the lowest sound pressure is sufficient for a hearing sensation. Below and above this range, hearing sensitivity decreases rapidly. The top curve represents the pain threshold. In this case, the sound pressure is large enough to inflict pain and, with longer exposure, causes permanent hearing damage. Certainly, the topic of loudness level and human hearing is large and cannot be fully covered in this paper; more reading, especially "Psychoacoustics: A Brief Historical Overview, Acoustics Today" can be recommended [10].

At this point, it might become clear already that hearing is, by a large degree, a matter of subjective perception. The determination of the loudness is complex and cumbersome.

So, the subjective measure of loudness is replaced by the objective measure of weighted sound pressure, as illustrated in Fig. 2. Here, the sound pressure is evaluated as a function of

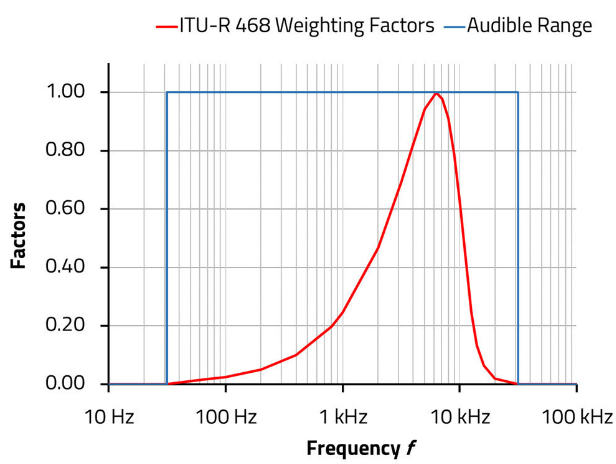

FIGURE 2. Graphic depiction of the filter factors for the unweighted audible range and frequency-dependent weighing factors $W_{ITU}(f)$ as suggested by ITU-R 468 [12].

frequency with a filter characteristic, shown in its normalized form in Fig. 2, which is approximately inverse to the isophons (curves of equal loudness) in Fig. 1 [12]. The normalized weighting filter curve, $W_{ITU}(f)$, in Fig. 2 is based on the recommendation of the International Telecommunication Union (ITU), and is applicable for filtering of pure tones. For the sake of clarity, Fig. 2 also contains a curve indicating an unweighted audible window.

Both, the weighted and unweighted filter curves, can be conveniently used to process audio signals.

The human dynamic range of hearing, from 130 dB (threshold of pain) to −9 dB (threshold of hearing), is significant. However, this wide span cannot perform these feats of perception at both extremes of the scale at the same time [13]. The ability to detect a slight distortion, superimposed to a fundamental or main signal very much depends on the frequency range and on the complexity of the main signal [4], [14], [15].

Investigations indicate that for the complex signal of speech and music, distortions of 2% to 5% can be introduced without being noticed by the listener [5], [13]. For single harmonic frequencies, it has been found that under laboratory conditions, human hearing is able to distinguish sound pressure distortions by single harmonics, in the range of 0.3% down to 0,01% (at 4 kHz, range of highest sensitivity), relative to the fundamental frequency [15].

To give an analogy for the corresponding differences in sound pressure level (see also section B): The distortion of 0.01% would compare to the ability to distinguish the sound of a trumpet (sound pressure level of 120 dB) in a distance of about 10 km, while standing 1 m away from another trumpet with the same pressure level [11], [9], [16]. Although this analogy simplifies and neglects the frequency spectra of the trumpets and differences between fundamentals and the harmonic, anyone may now understand how sensitive human hearing can be and how small a distortion of 0,01% actually is.

The lowest THDs, for the first 10 harmonics, from the above-mentioned human hearing experiment range in the order of about 10% to 7%, depending on the fundamental frequency. (Section A provides more information about THD.) Hence, under defined conditions, the hearing is able to detect THDs as low as 7%, which corresponds to a change in sound pressure level of 20 dB.

There is evidence that the THD is indeed not always the most accurate measure to predict the audibility of distortions in complex waveforms [3], [4], [5], [14]. A lower THD might not automatically imply a better sound quality for complex spectra with non-vanishing higher harmonics.

Multitoned signals or systems with disturbances at higher frequencies can be perceived differently in terms of subjective disturbance. For instance, it was found that a sin-wave driven loudspeaker (‘‘bad loudspeaker’’) with a THD of 2%, gives rise to a ‘‘Rub & Buzz’’ distortion, if the spectrum contains non-decreasing amplitudes of 0.3% at frequencies magnitudes higher than the fundamental [6]. That is to say, even the 20th harmonics and higher did not vanish. On the other hand, it was also found, that a loudspeaker (‘‘good loudspeaker’’) with a higher THD of 6%, but decreasing higher harmonics amplitudes, exhibits a low ‘‘Rub & Buzz’’ distortion and, thus, a better sound.

Hence, the loudspeaker with the high THD has a better sound than the loudspeaker with the low THD [6]. The fundamentals in this experiment have been at 200 Hz with higher harmonics stretching over a frequency range of several magnitudes. The higher harmonics, although as low as 0.3%, are in a frequency range (of about 5 kHz to 6 kHz) where the hearing is best, while the fundamental is at a frequency where the hearing is less sensitive. It is, therefore, plausible to theorize that the higher harmonics are perceived and experienced as disturbing by the listener under such conditions.

Another possible explanation is the masking phenomenon of one tone by another [4], [9]. Masking is a complex issue and has been studied for noise, complex and single tones as well as temporally shifted tones [9]. It describes the phenomenon when one test tone at a fixed frequency masks a different tone at a slightly different frequency. Tones close to fixed masking tones are usually less well perceived than tones at much higher frequencies. In other words, harmonics with much higher frequencies compared to the fundamental are not well masked by the fundamental and, thus, become audible [4].

For spectra that contain considerable components at higher frequencies, it is recommended to use methods such as the GeddLee metric or the use of an n-th harmonic weighting factor $n^2/4$ to measure the psychoacoustic influence of the high-frequency distortion [5]. Those metrics pronounce higher harmonic distortions, situated at frequencies several orders of magnitudes above the fundamental. However, if the spectrum shows harmonics with quickly declining amplitudes, those metrics provide no different results from THDs. In the case of the GeddLee metric, which utilizes the transfer function, it has even led to near zero and, thus, non-conclusive values [4].

As will be shown below, the amplitudes of capacitor-related harmonics decline much faster than $1/n^2$. Within 10 harmonics, amplitudes decline by a factor of 10^{-6} or so. Since higher harmonics are negligible due to their low intensity and the resulting transfer function is in good approximation linear, the THD is a suitable measure for this study [5].

To summarize the review on distortion metrics, the THD is a measure for systems that show low nonlinear disturbances that produce first harmonics below or about 1% and decrease to zero at higher harmonics. However, for larger nonlinear disturbances with non-vanishing higher harmonics, the THD might not give a correct measure for the audibility of disturbances.

III. INTRODUCTION OF CAPACITOR MODEL

This section introduces a model to check the plausibility of measured THD, presented in section VI. Section A briefly reviews the concept of THD, which is merely technical.

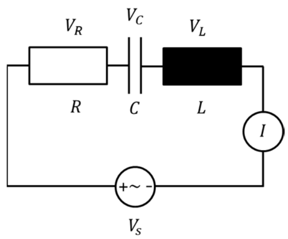

FIGURE 3. Fig. 1 Capacitor model consisting of equivalent series resistance *R*, capacitance *C*, equivalent series inductance *L*, ampere meter and voltage source.

Fig. 3 shows a circuit suitable to model a capacitor's voltage and current behavior. It consists of an equivalent series resistance (ESR) R, a pure capacitance C and an equivalent series inductance (ESL) L, modeling the capacitor, as well as a voltage source and an ampere meter.

Appling Kirchhoff's rule to the circuit in Fig. 3 leads to

$$V_s = V_R + V_L + V_C \tag{1}$$

with V_s as the time-dependent voltage signal applied by the source, V_R as the voltage drop over the ESR, V_L as the voltage drop over the ESL and V_C as the voltage drop of the pure capacitance.

The substitution of the voltages with

$$V_R = IR = RC\frac{dV_C}{dt} \tag{2}$$

and

$$V_L = L\frac{dI}{dt} = LC\frac{d^2}{dt^2} \tag{3}$$

yields

$$V_s = RC\frac{dV_c}{dt} - LC\frac{d^2V_c}{dt^2} + V_C. \tag{4}$$

The solution of equation (1) with the Ansatz

$$V_s(t) = V_0\cos(\omega t) \tag{5}$$

and

$$V_C(t) = ACos\left(\omega t + \phi\right), \tag{6}$$

were V_0 is the signal amplitude, ω is the angular signal frequency, A is a voltage amplitude and ϕ is the phase shift of the capacitor response, yields

$$I(t) = \frac{C\omega V_0}{\left(LC\omega^2+1\right)\cos(\phi) - RC\sin(\phi)}\cos\left(\omega t+\phi+\frac{\pi}{2}\right), \tag{7}$$

$$V_C(t) = \frac{V_0}{\left(LC\omega^2+1\right)\cos(\phi) - RC\sin(\phi)}\cos\left(\omega t+\phi\right), \tag{8}$$

$$V_L(t) = \frac{-LC\omega^2 V_0}{\left(LC\omega^2+1\right)\cos(\phi) - RC\sin(\phi)}\sin\left(\omega t+\phi+\frac{\pi}{2}\right), \tag{9}$$

as well as

$$\phi = \arctan\left(-\frac{RC\omega}{LC\omega^2+1}\right). \tag{10}$$

Equations (7) to (10) allow for a frequency shift; however, they do not contain oscillating terms with other frequencies than the signal frequency $\omega = 2\pi f$ (f with as ordinary frequency). Since the capacitor is not causing any harmonics, the THD is zero.

This, however, is only true for a capacitor that is independent of the applied voltage signal. To estimate the magnitude of the THD of a nonlinear capacitance the constant term C is replaced by a voltage-dependent capacitance

$$\begin{aligned} C\left(V,t\right) &= C_0\left(1 - aV_s\left(t\right)\right) \\ &= C_0\left(1 - aV_0Cos(\omega t)\right), \end{aligned} \tag{11}$$

where C_0 is the capacitance at zero volts and a a factor that governs the voltage dependence. By doing so, it is assumed that the capacitance is changed instantaneously upon the application of an external field, i.e. the dependence of the capacitance is proportional to $V_s(t)$.

This replacement of the capacitance leads to mixed terms of cosines and arctangents, which cause higher harmonics of the Fourier transform of the voltage V_C and V_L. The effect of the inductance, however, is for capacitors only present at high frequencies above angular frequencies of $(LC)^{-0.5}$. Usually, for electro-technical reasons, capacitors are operated below that resonance frequency. For capacitors with capacitances in the order of 100 μF and below and ESL values in the order of 10^{-9}H, this corresponds to frequencies in the MHz range and above. This frequency range exceeds the human hearing range. Due to psychoacoustics and electro-technical reasons, the term V_L can be neglected for the Fourier transformation. Hence, it is sufficient to consider the Fourier analysis of the pure capacitance-voltage response $V_C(t)$.

Equation (11) governs a factor for the magnitude of the voltage dependence; before any calculation, this value has to be set. The dc-voltage dependence for an electrolytic capacitor is, on average, never larger than 1%, as is exemplified for different types of electrolytic capacitors in Table 3, Table 4, and Table 5. This is at least true for the dc-voltage dependence. We continue under the assumption that the ac voltage drift of the capacitance is about the same magnitude as for the dc voltage measurements. This is probably an overestimation of the capacitance change at higher frequencies, since an electrochemical process that causes a change in capacitance might not occur at higher frequencies. The above-stated 1% change in capacitance with respect to the rated voltage, as shown in Fig. 4, can therefore be considered an upper limit.

The above-introduced model may now be used to numerically estimate the voltage response for specific voltage signals and thus the corresponding Fourier transformation.

IV. THD OF A CAPACITOR MODEL

In this section, the focus is on describing the frequency spectrum that a nonlinear capacitance would have, in case of single frequency excitation, i.e. single tone. With a voltage-independent capacitance, the ac voltages and currents in the introduced model (equations (7) to (10)) allow a frequency shift; however, they do not contain oscillating terms with other frequencies than the fundamental signal frequency. Due to the absence of higher harmonics, the THD of the transmitted signals is zero.

This changes, if the constant capacitance is replaced by a voltage-dependent term, i.e. non-linear capacitance (equation (11)). Based on measurements, the voltage-dependent capacitance change is estimated at about 1%, as illustrated in Fig. 4.

The result of the Fourier analysis, given in Fig. 5 provides, the normalized amplitudes of the harmonics for a specific fundamental frequency $\omega_0 = 2\pi f_0$, as given in equation (15). The calculation is made with $C = 470\mu$F, $R = 0.1\Omega$, $L = 510^{-8}$H. The model produces higher harmonic oscillations with the voltage-dependent capacitance as it is subjected to an oscillating voltage signal. The amplitude of the first harmonic is about 0.086%. The amplitude of higher harmonics decreases rapidly below 0.001%. According to the model, the frequency response results in a THD of 0.086%.

The model may not be able to accurately predict the amplitudes of harmonic frequencies because they depend on the capacitor's voltage dependence, which, in this case, is only estimated. However, it should provide an approximation of the actual amplitude of the THD and shows that the voltage-dependent capacitance results in non-zero harmonic distortion. Whether this is a "large" distortion for an audio application is answered using human hearing, which is reviewed in section II.

The first harmonics decay significantly and have a total harmonic distortion well below 0.1%, suggesting that this distortion is at or below the hearing threshold, with the latter being more likely.

In the further course of this article, measured harmonic distortions and electrical properties of various electrolytic capacitors are presented and discussed with the aid of that model.

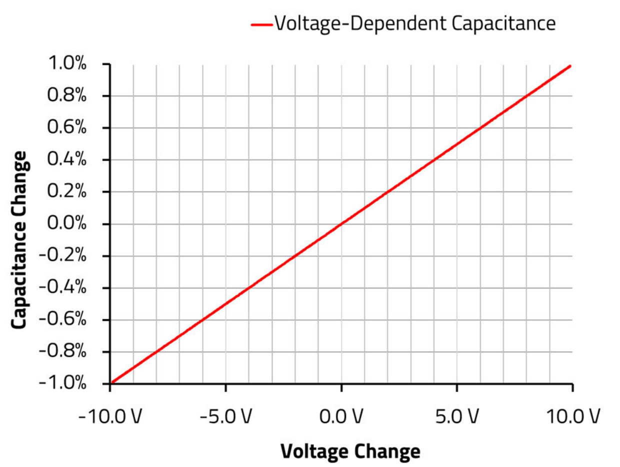

FIGURE 4. Dependence of the relative capacitance on the applied voltage change. Represents an upper estimate of actual measured capacitance-voltage dependence.

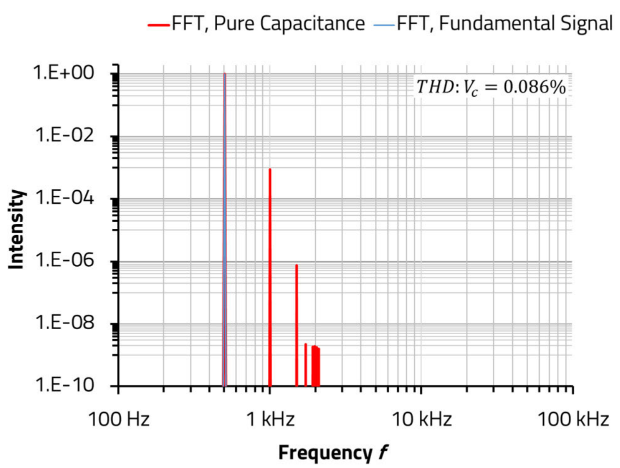

FIGURE 5. Calculated frequency spectrum of capacitor model with voltage-dependent capacitance, as shown in Fig. 4. The fundamental frequency is f_0= 500 Hz.

V. EXPERIMENTAL DETAILS

The study includes capacitors commercially available from eiSos Würth Elektronik (see Table 1) and purpose-built items manufactured at the production site (see Table 2). The sample batches in Table 2 have been prepared under near-mass production conditions at the production site. The samples represent variations in the composition of the separator paper, the density of the separator paper, the thickness of the separator paper, and the electrolyte composition. The paper was supplied by Nippon Kodoshi Corporation and the main components of the electrolyte are $\gamma-$butyrolactone, dimethyl carbonate and ammonium tetraborate tetrahydrate.[1]

TABLE 1. Overview of commercially available samples.

Sample Name	Series	Cap. [µF]	Rated Voltage [V]	Part Number
WE, ASLI	WCAP-ASLI	470	10	865080253012
WE, AT1H	WCAP-AT1H	470	10	860240275007

The capacitor assembly process starts with the etching and electrochemical anodic pre-forming of aluminum oxide. This etching and forming process increases the surface area of the

[1]To protect the intellectual properties of Würth Electronic (WE) further preparation details may not disclosed without the signing of a non-disclosure agreement.

TABLE 2. Overview of purpose-built items and variation of materials.

Sample Batch	Paper			Electrolyte	
	Thickness [um]	Density [g/cm^3]	Main Fiber Component	Water Content [%]	Cond. [mS/cm]
P1	40	0.45	Manila Hemp	18-21	14
P2	40	0.4	Manila Hemp	18-21	14
P3	40	0.35	Bast	18-21	14
P4	40	0.4	Manila Hemp	49-55	32
P5	30	0.66	Synthetic	18-21	14
P6	40	0.35	Bast	49-55	32

aluminum electrode and forms an insulating layer; the formation and etching have a crucial influence on the charge-storing abilities of the capacitor. After cutting the large foils into their product-specific size, the electrodes are connected to leads and rolled into a cylindrical form with a separator paper inserted between them. This assembly represents the capacitor unit, which is then impregnated with electrolyte and cased in an aluminum housing. The sealed capacitor is then subjected to a post-reform process, at which voltage is applied, to seal off minute defects in the oxide layer[1].

Since the etching and pre-forming process on a mass-product scale is complex, it would be extremely difficult to make variations of the electrodes in commercial devices [17]. However, it is possible to vary the electrolyte and the separator paper to influence the capacitor's electrical characteristics, as we have done in this study [18], [19].

For sample batches P1, P2 and P3, only the paper was changed to study its influence on the electrical properties. The influence of the water content in combination with different separator papers is to be investigated with the samples P4, P5 and P6. All capacitors, including the purpose-built items, are surface-mount devices with the same dimensions, types of casing and connections.

The measurements were conducted with the impedance analyzer Alpha-AK High-Performance Frequency Analyzer connected to the frontend POT/GAL, Electrochemical Test Station (15 V, 10 A) from Novocontrol in a four-terminal Kelvin configuration. The connection to the capacitor was made by Kelvin clamps. The connecting lines between the test station and the device under test (DUT) were chosen to be as short as possible with a length of around 20 cm in order to reduce the influence of parasitic inductances. The analyzer control as well as the harmonics acquisition were carried out with WinDETA Software (V 6.02) from Novocontrol, which runs on a Windows system as provided by Novocontrol.

Any subsequent data evaluation, as well as the model calculations, have been performed with Wolfram Mathematica 11. The ESR and capacitance values have been obtained by fitting a resistance-capacitance-inductance model to the impedance data.

Before the measurements, each sample was pre-poled for 20 minutes at its rated voltage (10 V) with HMP4040 programmable power supply from Rohde & Schwarz. ESR and capacitance were measured with a dc offset of 1 V and a probing ac signal amplitude of 0.1 V. For the THD measurements, the DC offset was 6 V and the probing ac signal amplitude was 1.5 V. The amplitude of the ac signal has been such as to maximize effects due to possible nonlinear capacitive behavior. For each sample batch, at least five capacitors have been measured.

VI. MEASURED THD OF 470 μF ELECTROLYTIC CAPACITOR

This section explains the frequency analysis using the example of an electrolytic capacitor from Würth Electronic with a capacity of 470 μF (865080253012). It includes the calculation of the THD and introduces the average THD as a quality measure for the signal distortion at the capacitor.

For the measurement of the harmonic, an ac probing voltage signal, with a frequency f_0, is applied to the capacitor, which in turn causes a current that leads to charging/discharging of the capacitor. The voltage across the capacitor measured with separate test leads can now be analyzed using a Fast Fourier Transform (FFT) to obtain a frequency spectrum of the measured voltage response of the capacitor. In this measurement, the applied frequency f_0 is the lowest possible frequency and, thus, the fundamental frequency.

The measured frequency spectrum of a capacitor with the fundamental frequency of 448.9 Hz, in Fig. 6, shows a steep decline in amplitudes for higher harmonics, which is

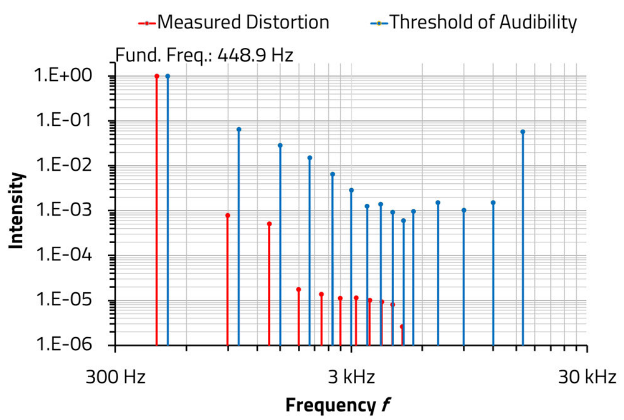

FIGURE 6. Measured frequency spectrum of 470 μF aluminum electrolytic capacitor (WCAP-ASLI, 865080253012) at fundamental frequency of voltage signal is 448.9 Hz. Also shown is, threshold of audible distortions as determined in psychoacoustic experiment for a fundamental at 500 Hz. [15].

typical for all studied capacitors and excitation frequencies (see Fig. 13 section B). The amplitudes of the first two harmonics are decreasing to values well below 0.1% compared to the fundamental signal. The higher-order harmonics attain values in the order of 0.001% and below. All amplitudes of the harmonics are well below the threshold of audibility, which is also plotted in Fig. 6. The displayed hearing threshold values have been taken from a study about the relation between harmonic distortion and human auditory sensation [15]. The values were determined in a psychoacoustic masking experiment at a fundamental at 500 Hz (see section B for low-frequency example). Studies about masking of one tone by another, given in other literature, corroborate the presented threshold of audiblity [9]. There appears to be no evidence that the measured distortions in the case of pure tones are audible. For the sake of thoroughness, it shall be mentioned that the results cannot be simply transferred to cases of complex or temporally shifted tones.

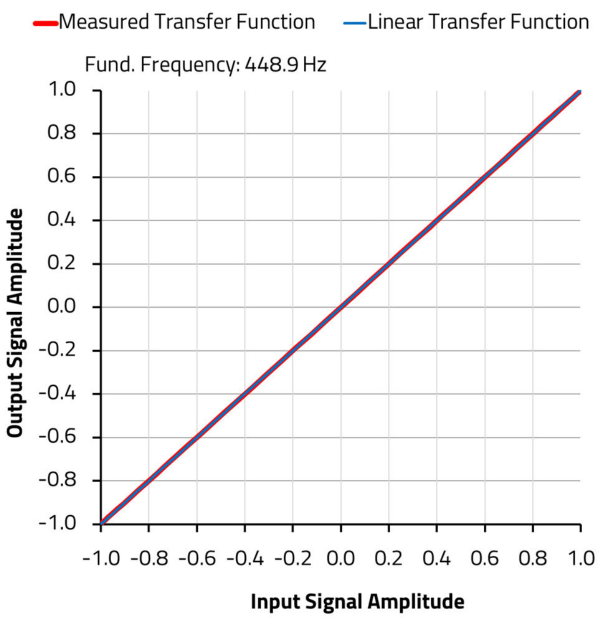

FIGURE 7. Linear and measured transfer function of a 470 μF aluminum electrolytic capacitor (WCAP-ASLI, 865080253012). Fundamental frequency of voltage signal is 448.9 Hz.

Due to the low amplitudes of the harmonics, the corresponding transfer function, given in Fig. 7, shows a practically perfect linear behavior. The corresponding amplitude of the superimposed disturbance is about a factor of 1000 smaller than the fundamental itself. One can therefore argue that the capacitor represents a linear system to a good approximation.

Other measurement quantities like the GeddLee metric or metrics that involve the emphasis on higher harmonics will not provide further information [5]. The GeddLee metric involves the second derivative of the transfer function, which for capacitors is in good approximation zero and higher harmonics beyond the 10^{th} harmonic show declining amplitudes below 0.001%, which can be neglected. As discussed in section II, the THD is a suitable measure for the comparative study of distortion under these conditions.

Taking the model calculations, given in sections III and IV, the frequency response of the capacitor is as expected and thus plausible. The order of magnitude of the first harmonic, as well as the steep decline for higher harmonics, agrees with the model calculation shown in Fig. 5. The THD (details given in section A) calculated based on the Fourier transformation in Fig. 6 yields a value of 0.078%, which compares roughly to the theoretical value of 0.086%, calculated in section III.

The THDs for different fundamental frequencies f_0 in the 1 Hz to 1 MHz range, given in Fig. 8, show variations in the range of 0.001% to 0.4%. In this graph, each point represents the THD measured at a certain fundamental frequency $f = f_0$. So, each point in Fig. 8 represents the THD measured for FFTs as exemplarily presented in Fig. 6. This THD spectrum, denoted as THD (f), shows by trend lower THD values at low frequencies and larger THD values at high frequencies. In the further course of the discussion, subscript "0" will be dropped since THD (f) will provide the THD value at different fundamental frequencies; thus $f = f_0$.

The values within the audible range are around 0.05% or so. This spectrum is a representative example and shows the same characteristics measured for other samples. (see also Fig. 13 in section B) However, for the following discussion, the spectrum, measured for a range of fundamental frequencies in the audible range, still contains too much information. The following discussion shall not focus on specific features, measured for certain fundamental frequencies; however, it will focus on the overall magnitudes of the measured THDs.

To obtain a figure of merit for the frequency distortion within the audible range $\Delta f = f_2 - f_1$, we calculate the

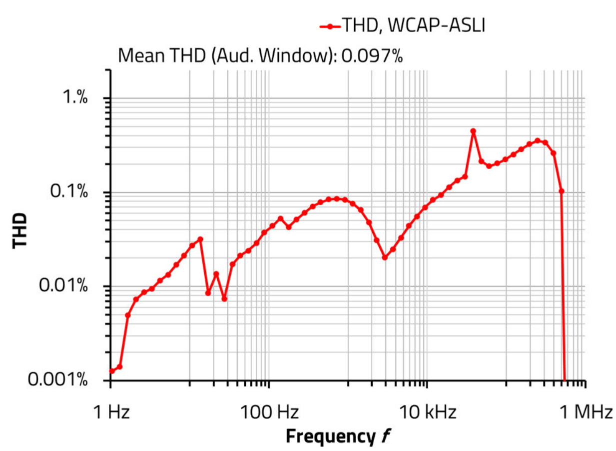

FIGURE 8. THD(f) of 470 μF aluminum electrolytic capacitor (WCAP-ASLI, 865080253012), measured at different fundamental frequencies in a range from 1 Hz to 1 MHz.

average

$$\mathrm{THD}_{\mathrm{Mean}} = \frac{1}{f_2 - f_1} \int_{f1}^{f_2} \mathrm{THD}(f)\, df \tag{12}$$

as well as the weighted average

$$\mathrm{THD}_{\mathrm{ITU}} = \frac{1}{f_2 - f_1} \int_{f1}^{f_2} W_{ITU}(f) \times \mathrm{THD}(f)\, df \tag{13}$$

on the basis of the human hearing sensitivity $\mathrm{W}_{\mathrm{ITU}}(f)$ and the measured THD spectrum $\mathrm{THD}(f)$. The weighted mean $\mathrm{THD}_{\mathrm{ITU}}$ takes the hearing sensitivity into account while $\mathrm{THD}_{\mathrm{Mean}}$ gives the unweighted mean of the function $\mathrm{THD}(f)$. $\mathrm{THD}_{\mathrm{ITU}}$ is introduced to enable discussion of how the perception of distortion is affected by hearing sensitivity. For the given example, the averages are: $\mathrm{THD}_{\mathrm{Mean}} = 0.097\%$ and $\mathrm{THD}_{\mathrm{ITU}} = 0.017\%$. The weighted average is lower, since human hearing is less sensitive below 1 kHz and above 10 kHz.

As discussed in section II, the hearing threshold for distortions is about 7%, especially if the amplitudes of the harmonics decline towards zero, as they do in the example shown. Hence, the harmonic distortions of the studied capacitor are by orders of magnitudes below the auditory perception.

Based on these results, capacitors are unlikely to be a significant source of distortions if used for signal coupling (series connection) or decoupling (parallel connection) in audio applications. The transfer functions of amplifiers show, by design, higher nonlinearities than capacitors [1], [20], [21]. It cannot be entirely ruled out that clipping or other strong non-linear effects of power amplifiers may lead to amplification of capacitor-related minuscule distortions up to the point where they become clearly audible.

The further investigation of such effects exceeds the scope of this work. Future studies of this effect would have to separate the high distortions incited by the clipping itself from those caused by the capacitor.

VII. COMPARATIVE ANALYSIS OF CAPACITORS

Section VI exemplified the Fourier analysis on a single capacitor and introduced the average THD values $\mathrm{THD}_{\mathrm{Mean}}$ as well as $\mathrm{THD}_{\mathrm{ITU}}$ as a measure for the overall frequency distortion within the audible range. In the following section, the $\mathrm{THD}_{\mathrm{Mean}}$ as well as $\mathrm{THD}_{\mathrm{ITU}}$ are used to quantify the influence of different electrolyte compositions and separator paper on the signal distortion.

Fig. 9 and Fig. 10 show the average capacitance and ESR values of the different capacitors, respectively. As stated in section V, Würth Elektronik (WE) samples are commercially available. For the sample batches P1 to P6, the water content of the electrolyte, as well as the paper, was systematically varied. All samples have rated capacitances of 470 μF, within the customary tolerances of $\pm 20\%$, as illustrated in Fig. 9.

As displayed in Fig. 10, the ASLI samples have the lowest ESR value among the commercially available products, since they are from a designated low-loss product line. The sample batches P1 to P3 show a further decrease of the ESR compared to the ASLI samples as the density of the separator paper is decreased. This effect is related to the increasing mobility of the electrolyte, due to the increasing pore size of the separator paper.

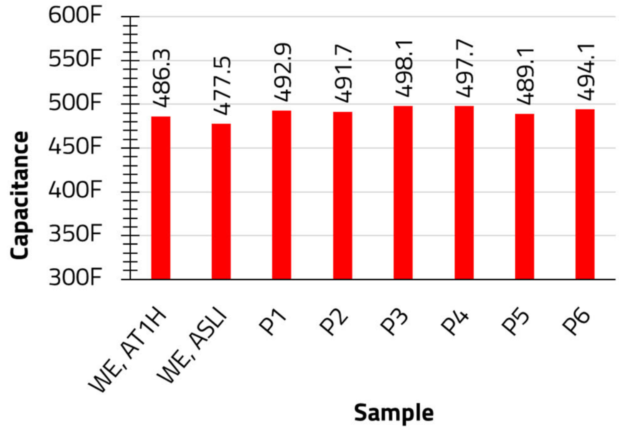

FIGURE 9. Average values of measured capacitances.

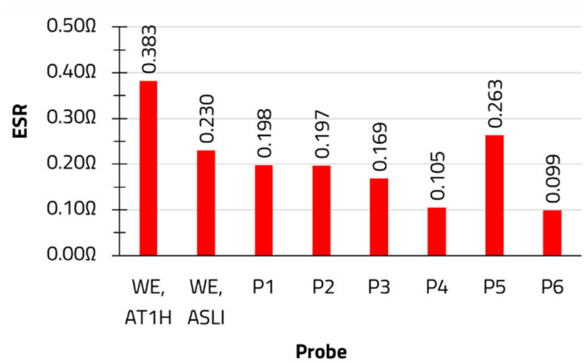

FIGURE 10. Average values of ESR.

For sample batch P4, the paper and the electrolyte were chosen with the aim of obtaining a further decrease of ESR. For sample batch P6, the paper density has been further lowered, resulting in a further ESR decrease compared to samples of batch P4. P5 illustrates the effect of a high-density paper on the ESR, which has a larger ESR than samples P1 to P3.

In fact, there is more to say about the influence of electrolytic and separator paper on ESR, but for now, it is enough to say that the capacitors presented cover a wide range of electrolytic and separator papers. Interestingly, the effect of these material variations and differences in ESR values on the $\mathrm{THD}_{\mathrm{Mean}}$ as well as $\mathrm{THD}_{\mathrm{ITU}}$, plotted in Fig. 11, is practically neglectable, as the mean range, indicated by the error bars, suggests.

$\mathrm{THD}_{\mathrm{Mean}}$ is well below 7%, indicating that the harmonic distortions are not audible. In general, the $\mathrm{THD}_{\mathrm{ITU}}$, which takes into account the frequency-dependent human auditory sensitivity, is an order of magnitude lower than the $\mathrm{THD}_{\mathrm{Mean}}$.

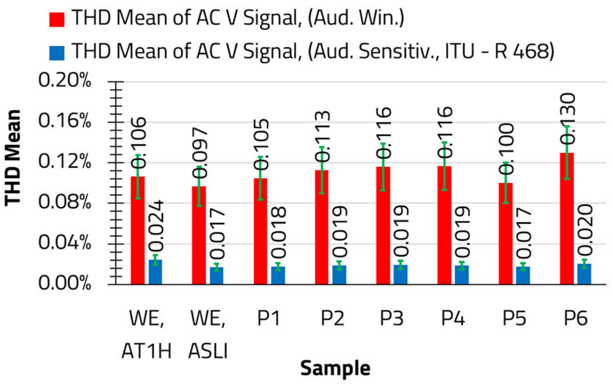

FIGURE 11. Measured THD_{Mean} (audible window) and THD_{ITU} (audible sensitivity) values. Error bars indicate the mean range of values.

This creates strong evidence against the audibility of the distortions.

The THD_{Mean} and THD_{ITU} of the AT1H compared to P1 is nearly unchanged, although the ESR value of P1 is markedly decreased compared to AT1H.

The effect of material variations on the THD can be seen in the comparison of sample batches P3 and P4. Here paper and electrolyte have been changed with no noticeable effect on THD_{Mean} and THD_{ITU}. Similar could be found in the comparison of sample batches P2 and P3, which contain different separator papers but the same electrolyte.

A different THD_{Mean} can be found for samples P5 and P6. The sample batch P5 with the high ESR and the large paper density has a lower THD_{Mean} than P6 with a low ESR and low paper density. This could suggest an inversely proportional relation between ESR and THD_{Mean}. However, that inverse proportionality cannot be confirmed for samples AT1H and P5. The THD_{Mean} for those two is nearly the same. However, when focusing on the frequencies of high audible sensitivity, the changed THD_{ITU} for the above-discussed AT1H and P5 would suggest a direct proportionality.

Hence, it is difficult to identify the cause for the small variations of THD_{Mean}.and THD_{ITU}. In fact, as indicated by the error bars, the differences between most measurements are of low statistical significance. Thus, the separator paper and electrolyte variations do not significantly impact the THD, in this study. This result is confirmed by another study conducted on various capacitors, which also found no significant differences in the level of distortion [1].

VIII. CONCLUSION

This study has investigated the ESR, capacitance and THD of eight different capacitor types. While the commercial capacitors as well as the material variations of batch P1 to P6 have shown changes in ESR, none of them has shown significant changes of the THD_{Mean} as well as THD_{ITU}. The plausibility of the THD value for a fundamental frequency of 500Hz has been checked against model calculations. Furthermore, it was exemplarily shown that the amplitudes of the higher harmonics are well below the hearing threshold.

The unweighted THD_{Mean} was about 0.1% and the weighted THD_{ITU}, which suppresses less audible harmonics in accordance with ITU-R 468, was about 0.02%. Even the THD_{Mean}, which includes THDs from less audible frequencies, suggests that the harmonics distortions are well below the threshold of audibility, which is at about 7%. In the highest audible sensitivity range, the THD values of THD_{ITU} are even 10 times smaller than the values of THD_{Mean}.

From this, it can be concluded that the electrolytic capacitors do not cause significant distortions of the fundamental frequencies when transmitting signals and can, therefore, be considered as linear devices to a good approximation. Modifications of the electrolyte or the separator paper have a negligible influence on the THD. Hence, this study suggests that any electrolytic capacitor is potentially suitable for audio applications. The model calculations even suggest that any capacitor with a constant capacitance-voltage behavior is suitable for audio applications. It is likely that other voltage-independent types of capacitors and passive components, in general, produce similarly low distortion amplitudes compared to the hearing threshold.

One could speculate that other effects, such as vibrations caused by sound waves transmitted from the circuit board to the capacitor assembly, could interfere with the audio signal and thus affect the audio quality [2]. Masking effect with complex or temporally shifted tones may also lead to different results in terms of audibility. However, those questions need to be the subject of further research.

Arguably, the electrode properties, such as porosity, might also influence the electrical properties. However, since electrode foil production is complex, their influence cannot be studied in commercial products. A study on the influence of the electrodes (such as porosity etc.) is best carried out in laboratory experiments.

Consequently, it is feasible to speculate that the choice of non-linear devices such as op-amps and diodes probably has a more significant impact on the audio quality of the amplifier, i.e., the overall distortion characteristics, than the choice of electrolytic capacitor [1]

APPENDIX

A. REVIEW OF THD AND FOURIER TRANSFORMATION

Audio signals may be characterized by parameters such as frequency bandwidth and signal level. With analog audio signals, the signal level, usually given in decibels (dB), corresponds directly to the amplitude of the electrical voltage, which in turn is proportional to the sound pressure. From an electrical point of view, an audio signal is an oscillating current often in the human audible range with a maximum voltage. Any sound signal can be represented as a superposition of harmonic oscillations. Each of the oscillation has its specific frequency and amplitude.

The mathematical process of discretizing arbitrary signals into harmonic oscillations is performed with the Fourier

TABLE 3. Measurements taken at 120 Hz of: Series: WCAP-ATG8, 860010672001, 100 nF, AC-Level: 1 V, Keysight E4980A, Fixture: 16065A.

DC Voltage [% of V_r]	C [nF]	ΔC [%]
0	90.256	0.000
2	90.198	-0.064
4	90.166	-0.099
6	90.138	-0.130
8	90.117	-0.154
10	90.095	-0.177
20	90.071	-0.204
30	90.076	-0.198
40	90.109	-0.161
50	90.161	-0.105
60	90.226	-0.033
70	90.301	0.051
80	90.383	0.142
90	90.470	0.238
100	90.559	0.337

transform (or Fourier analysis). Any time-dependent signal $F(t)$ may be represented by a Fourier series

$$F(t) = a_0 + \sum_{k=1}^{\infty} a_k \sin(k\omega_0 t) + \sum_{k=1}^{\infty} b_k \cos(k\omega_0 t) \tag{14}$$

where a_0 is a constant offset, $\omega_0 = 2\pi f_0$ the fundamental frequency, k is the index number, and a_k as well as b_k are Fourier coefficients. The first harmonic oscillation ($k = 1$) is also referred to as the fundamental or fundamental signal. It is the signal with the lowest harmonic frequency in the sum of harmonically related signals.

Fourier coefficient may be used to calculate the total harmonic distortion (THD) of a signal

$$\mathrm{THD} = \sqrt{\frac{\sum_{k=2}^{\infty} (a_k^2 + b_k^2)}{a_1^2 + b_1^2}} = \sqrt{\frac{\sum_{k=2}^{\infty} |c_k|^2}{|c_1|^2}} \tag{15}$$

with c_k as the amplitude of the k-th harmonic [22], [23]. The THD, as well as its above-used averages $\mathrm{THD}_{\mathrm{mean}}$ and $\mathrm{THD}_{\mathrm{ITU}}$ provide a measure of signal distortion in comparison to the fundamental frequency signal.

B. CALCULATIONS, TABLES AND NOTES

To calculate sound pressure attenuation L_2 over distance for a point sound in an anechoic environment:

$$L_2(r_2) = L_1(r_1) - 20\log_{10}\left(\frac{r_2}{r_1}\right) \tag{16}$$

where $L_1(r_1)$ is the known sound pressure level at distance r_1 and $L_2(r_2)$ is the unknown sound pressure level at the second distance r_1 [9].

TABLE 4. Measurements taken at 1 kHz of: Series: WCAP-ASLU, 865090640001, 100 nF, AC-Level: 1 V, Keysight E4980A, Fixture: 16065A.

DC Voltage [% of V_r]	C [nF]	ΔC [%]
0	107.346	0.000
2	107.281	-0.061
4	107.261	-0.080
6	107.218	-0.122
8	107.154	-0.181
10	107.095	-0.237
20	107.032	-0.296
30	107.044	-0.284
40	107.095	-0.238
50	107.171	-0.167
60	107.267	-0.078
70	107.378	0.026
80	107.504	0.143
90	107.643	0.273
100	107.796	0.415

TABLE 5. Measurements taken at 120 Hz of: Series: WCAP-ASLI, 865080253012, 470 μF, AC-Level: 0.2 V, impedance analyzer Alpha-AK, POT/GAL from Novocontrol in a four-terminal Kelvin configuration.

DC Voltage [% of V_r]	C [μF]	ΔC [%]
0	465.552	0.000
2	465.117	-0.093
4	464.741	-0.174
6	464.436	-0.240
8	464.174	-0.296
10	463.910	-0.353
20	463.070	-0.533
30	462.433	-0.670
40	462.456	-0.665
50	462.810	-0.589
60	463.682	-0.402
70	464.843	-0.152
80	466.137	0.143
90	467.913	0.507
100	469.796	0.912

Example: Trumpet [16]

$$L_1(r_1) = 120\ \mathrm{dB}$$
$$r_1 = 1\mathrm{m}$$
$$L_2(r_2) = 40\ \mathrm{dB}$$
$$r_2 = 10\ \mathrm{km}.$$

TABLE 6. The characteristics of auditory sensation threshold at various harmonics of a fundamental frequencies = 500 Hz. Each signal amplitude above the 1st fundamental is at the auditory sensation threshold. [15] The values for the 6th, 8th, 9th and 11th harmonic have been obtained by interpolated and used for the THD calculation.

No.	Freq. [Hz]	diff. Values [dB]	Value [dB]	Values [%]
1	500	90	90	100.000
2	1000	-23.7	66.3	6.531
3	1500	-30.8	59.2	2.884
4	2000	-36.3	53.7	1.531
5	2500	-43.7	46.3	0.653
6	3000	-50.8	39.2	0.288
7	3500	-57.9	32.1	0.127
8	4000	-57.1	32.9	0.140
9	4500	-60.75	29.25	0.092
10	5000	-64.4	25.6	0.060
11	5500	-60.35	29.65	0.096
14	7000	-56.3	33.7	0.153
18	9000	-59.8	30.2	0.102
24	12000	-56.3	33.7	0.153
32	16000	-24.7	65.3	5.821

The relative sound pressure between the sound pressure values p_1 and p_2, corresponding to L_1 and L_2, respectively, is

$$\frac{p_2}{p_1} = \frac{10^{\frac{l_2}{20}}}{10^{\frac{L_1}{20}}} = \frac{10^{\frac{120\mathrm{dB}}{20}}}{10^{\frac{40\mathrm{dB}}{20}}} = 0.0001 = 0.01\%. \quad (17)$$

The relative change in the sound pressure level given in this example calculation for two trumpets at a distance of 1 m and 10,000 m is 0.01%.

The harmonics, given in Table 7 and Table 6, are at the auditory sensation threshold and have been determined in a psychoacoustic experiment by Lin [15] In this experiment, the test listener heard the fundamental frequency at 90 dB. Each individual harmonic could be superimposed individually. The listener then adjusted the volume of the harmonic frequency to the hearing threshold.

The corresponding THD for those harmonics are about 10%. The THD of the first 10 harmonics are 9.4% and 7.3% for fundamentals of 50 Hz and 500 Hz, respectively. In correspondence to the auditory sensitivity, the amplitudes are smallest at 5 kHz and increase toward low and high frequencies. The values in the Table 7 are inversely proportional to the trend of the ITU-R 468 filter curve in Fig. 2 in section II and, thus, reflect the sensitivity of the human ear.

The comparison of the percentage decrease of amplitudes in Table 6 and Fig. 6 shows that the harmonics of the capacitor (fundamental frequency about 500 Hz) are well below the auditory perception. The same result is found when comparing the amplitudes measured at fundamental about 50 Hz, given in Table 7 and Fig. 12.

TABLE 7. The characteristics of auditory sensation threshold at various harmonics of a fundamental frequencies = 500 Hz. Each signal amplitude above the 1st fundamental is at the auditory sensation threshold. [15] The values for the 6th, 8th, 9th and 11th harmonic have been obtained by interpolated and used for the THD calculation.

No.	Freq. [Hz]	diff. Values [dB]	Value [dB]	Values [%]
1	50	90	90	100.00
2	100	-21.2	68.8	8.7096
3	150	-30.5	59.5	2.9854
4	200	-36.2	53.8	1.5488
5	250	-40.8	49.2	0.9120
6	300	-46.2	43.8	0.4898
7	350	-51.6	38.4	0.2630
8	400	-57.65	32.35	0.1311
9	450	-58.225	31.775	0.1227
10	500	-58.8	31.2	0.1148
11	550	-61.25	28.75	0.0866
14	700	-63.7	26.3	0.0653
20	1000	-67.9	22.1	0.0403
28	1400	-71.5	18.5	0.0266
60	3000	-77.2	12.8	0.0138
80	4000	-77.8	12.2	0.0129
100	5000	-76	14	0.0158
132	6600	-73	17	0.0224
240	12000	-54.9	35.1	0.1799
320	16000	-25.6	64.4	5.2481

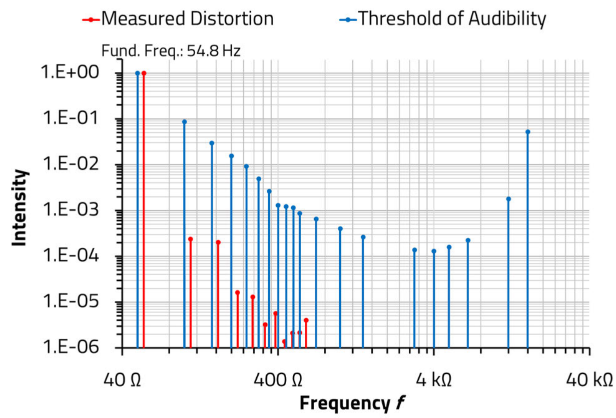

FIGURE 12. Measured frequency spectrum of 470 μF aluminum electrolytic capacitor (P4) at fundamental frequency of 54.8 Hz (ac voltage signal). Also shown, threshold of audible distortions as determined in psychoacoustic experiment for a fundamental at 500 Hz [15].

Fig. 13 shows exemplary FFT spectra of representatives of each sample batch at a fundamental frequency of 448.9 Hz. It was found that not only for this fundamental frequency, but also for other fundamental frequencies, the amplitudes of the corresponding harmonics decrease with frequency.

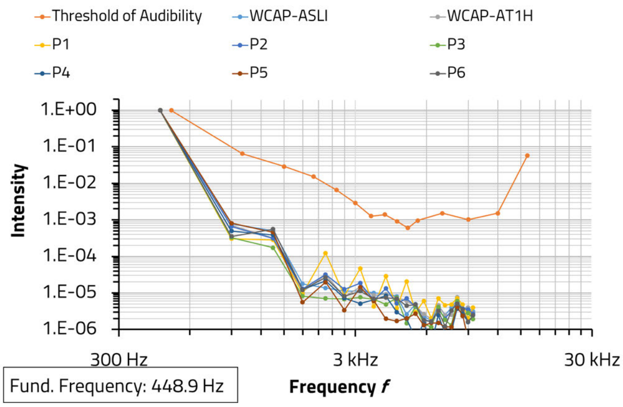

FIGURE 13. **Normalized 20 harmonics of different capacitor samples, measured for a fundamental frequency of 448.9 Hz. Also shown is, threshold of audible distortions as determined in psychoacoustic experiment for a fundamental at 500 Hz [15].**

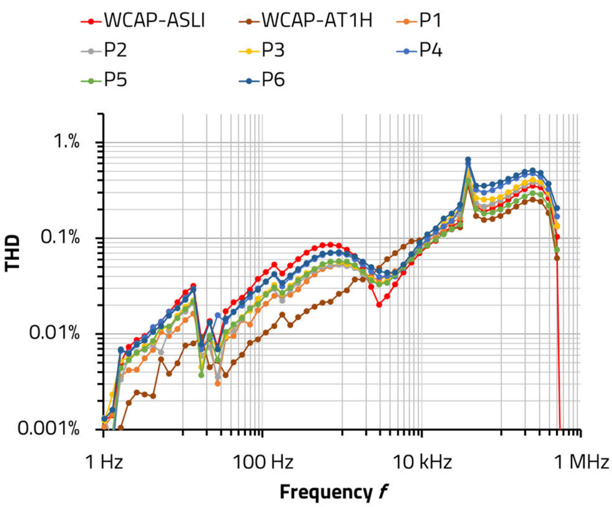

FIGURE 14. **THDs of different capacitor samples, measured at different fundamental frequencies in a range from 1 Hz to 1 MHz.**

Fig 14 shows exemplary THD measurements of the capacitors, used to calculate the THD_{ITU} and THD_{Mean}. It is noticeable that all measured THD spectra show a similar progression. For all measurements, the THD values increase with frequency and are about the same order of magnitude.

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RENÉ KALBITZ studied physics at the University of Potsdam and the University of Southampton (GB). After completing his diploma degree, he gained the Ph.D. degree in the field of organic semiconductors and insulators at the University of Potsdam. He gained further experience in the field of applied research with the Fraunhofer Institute for Applied Polymer Research. He has been the Product Manager of supercapacitors with Würth Elektronik, Berlin, since 2018, and oversees research and development projects in the field of capacitors.