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Evaluating Electrolytic Capacitors Specified for Audio Use: A Comparative Analysis of Electrical Measurements and Capacitor Distortion Products in Line Level Interstage Coupling Applications

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This paper provides a number of comparative, quantitative evaluations of 10 different makes and models of electrolytic capacitors. Models range from expensive parts specified for use in audio circuits to low-cost general-purpose parts. The datasets comprise out-of-circuit electronic measurements, total harmonic distortion (THD) fast Fourier transform (FFT) sweeps, and cumulative distortion products resulting from 31-tone stimulus performed on the components in a circuit designed to emulate a typical line-level audio recording and mixing console. Results are examined in an effort to identify any measurable properties that may distinguish "audio capacitors" as outliers from their general-purpose counterparts.

0 INTRODUCTION

This paper emerged as a result of exploring options for replacing interstage coupling capacitors in an analog mixing console from the early 1980s. Upon examining options for suitable replacement capacitors, it quickly became clear that there are as many opinions about the "sound" and "performance" of electrolytic capacitors in this application as there are makes and models of capacitors. There is, however, a dearth of empirical data supporting assertions of any quantifiable difference between any two or more makes/models of electrolytic capacitors, particularly in series configuration (direct current [DC]-blocking applications) within "real-world" line-level audio circuits, which are likely to contain many capacitors in-circuit.

At this point, it is well known that all capacitors introduce nonlinear distortions into audio circuits and that electrolytic capacitors in particular introduce measurably more distortion than film and NP0 ceramic types. [1], [2], [3]

Previous work has demonstrated that both the presence of high DC bias voltage across a capacitor and higher signal level can increase capacitor distortion in shunt and series configuration [1], [2] and that increasing capacitance values in series DC-blocking applications will lower distortion [2]. Line-level audio devices designed around operational amplifiers, however, are unlikely to encounter DC offsets beyond a few hundred millivolts.

Bateman has also demonstrated that the practice of placing film capacitors in parallel with electrolytic capacitors in DC-blocking applications does not reduce distortion in a quantity significant enough to justify the additional cost and Printed Circuit Board area [1], in spite of continued insistence to the contrary on a number of internet forums and the employment of this technique in a number of contemporary audio circuit designs.

Additionally, a number of electrolytic capacitor manufacturers establish claims of superior audio performance, specifically marketing their components as high-quality audio types to high-end consumer and professional audio markets. These claims are not new and have been addressed in previous work. As might be expected, these products tend to cost significantly more than "general-purpose" components.

Manufacturer-provided datasheets for these products provide no evidence to support these claims or justify the additional cost. This provides a conundrum for the audio electronics designer developing line-level circuits in which significant DC bias voltages are not likely to be a concern: All other factors being equal, does the more expensive "audio-type" capacitor outperform the general-purpose type in any measurable way? Do manufacturers' claims of superior performance in audio circuits justify the added cost to audio product development? These considerations are perhaps more significant for designers of analog consoles, in which hundreds of capacitors may be necessary, and capacitor cost might represent a significant build cost issue.

Bateman and Self have demonstrated that there is not necessarily any correlation between capacitor cost and low distortion in both shunt and series configuration [1], [2], but subjectivists continue to insist (particularly in a number of hi-fi and do-it-yourself [DIY] audio internet forums) that capacitor X “sounds better” than capacitor Y without providing any empirical evidence to substantiate their claim.

While this paper does not address perceptual factors, it does aim to definitively demonstrate that there are no measurably significant differences in cumulative distortion products among 10 identical test circuits employing different models of electrolytic capacitors—ranging from low-cost general-purpose types to more expensive types specified for audio use—in interstage coupling applications within a real-world line-level audio circuit developed around operational amplifiers.

1 EXPERIMENT DESIGN AND METHODOLOGY

Ideally, testing would be performed on a number of identical analog audio consoles, each differing only in the make and model of DC-blocking capacitors employed. Naturally, this is unfeasible. Another option might be to “re-cap” one or more channels of a single console with several varieties of capacitor and perform tests only on those channels. Without a willing console donor, this method is also unfeasible, so a different approach was needed.

1.1 Capacitor Selection

Twenty-six of each of 10 makes/models of electrolytic capacitor were purchased from Mouser Electronics. All capacitors have an advertised value of 100 uF/25 V and range in price from $0.064 USD to $1.97 USD per unit when purchased in quantities of 100.

The 100 uF/25 V value was selected as having both a reactance outside the audible spectrum and ready availability in large quantities from Mouser at this particular value.

Makes and models were selected based on the following criteria:

- Ready availability in quantity.
- The most expensive and least expensive available from Mouser in quantity must be represented.
- A minimum of two different brands of audio-specific capacitor must be represented.
- There must be one each audio-specific and general-purpose bipolar type.
- There must be at least one axial-leaded capacitor.
- At least one “exotic” dielectric, in this case the ELNA RFS “Silmic II” with silk fiber dielectric, and one organic polymer dielectric must be represented.

Table 1. Capacitors tested, cost per piece, cost per 100 units.

Capacitor	Cost/1 pc.	Cost/100 pcs.
ELNA RFS*	$0.80	$0.402
Lelon REA	$0.10	$0.064
Nichicon ES*	$0.75	$0.347
Nichicon KZ*	$0.62	$0.379
Nichicon NS†	$2.89	$1.860
Nichicon VZ	$0.23	$0.133
Panasonic FC	$0.29	$0.122
Panasonic FM	$0.29	$0.120
Panasonic SU	$0.58	$0.271
Vishay/BC ASM	$1.08	$0.683

*Denotes part specified for audio use
†Available at significantly lower cost at 100 uF/20 V

Remaining capacitors were selected arbitrarily. Capacitor selection and cost, as of publication date, are shown in Table 1.

1.2 Out-of-Circuit Electrical Testing

Prior to soldering the capacitors onto printed circuit boards for audio testing, each capacitor was individually numbered and measured for capacitance and dissipation factor (tan delta) to ensure that each component tested “good” and that measured capacitance was within manufacturer-stated tolerance. Both measurements were taken at 120 Hz as recommended by International Electrotechnical Commission 60384-1:2016.

Individual measurements were logged in an Excel spreadsheet. Capacitance for each capacitor model was then averaged, and standard deviation calculated (Table 2) to perhaps provide some insight into the precision of component manufacture. Since all capacitors were purchased simultaneously from the same supplier, it is safe to assume all pieces of each make and model come from the same batch.

Dissipation factor, a standard measurement performed by manufacturers [1] was also measured at 120 Hz, logged, and averaged for each model, and standard deviation was calculated. Results shown in Table 3.

While all capacitors tested well within the stated ±20% tolerance, the Elna Silmic II was consistently closest to 100 uF with an average capacitance of 100.14 uF. Standard deviation shows a tight grouping with $p = 0.57$. Panasonic SU bipolar capacitors showed the tightest grouping overall with $p = 0.53$, though average capacitance was a bit high at 108.53 uF. Nichicon VZ deviated furthest from 100 uF with an average capacitance of 91.06 uF, while the Nichicon NS showed the weakest grouping with $p = 1.68$.

All capacitors tested well below stated dissipation factor values, with the Nichicon NS showing the lowest overall. As dissipation factor is proportional to equivalent series resistance (ESR), this makes sense, as very low ESR is a well-known characteristic of conductive polymer electrolytic capacitors. Standard deviation is remarkably low with $p \leq 0.005$ for all models, the ELNA RFS displaying the tightest grouping with p at just over 0.00082.

Table 2. Rated capacitance vs. measured, averaged capacitance.

Capacitor	*C*, Rated	*C*, Measured Avg.†	Standard Deviation
ELNA RFS*	100 μF	**100.14**	0.57
Lelon REA	100 μF	100.87	1.18
Nichicon ES*	100 μF	95.15	0.69
Nichicon KZ*	100 μF	95.08	0.98
Nichicon NS	100 μF	98.86	1.68
Nichicon VZ	100 μF	91.06	0.96
Panasonic FC	100 μF	95.55	0.58
Panasonic FM	100 μF	91.20	1.22
Panasonic SU	100 μF	108.53	**0.53**
Vishay/BC ASM	100 μF	91.67	1.28

*denotes capacitors specified for audio use
†Twenty-six of each capacitor type measured at 120 Hz, results averaged.

It is worth mentioning that dissipation factor and ESR show no apparent correlation to audio quality and distortion performance. [1]

1.3 In-Circuit Audio Testing

Each group of 26 capacitors was then soldered into place on one of 10 identical printed circuit boards—with each of these circuit boards loaded onto a motherboard—and subjected to a battery of tests and measurements within a line-level audio circuit.

1.3.1 The Test System

In an effort to provide a test circuit representative of a "real-world" audio circuit, a bespoke test system was designed (Fig. 1) to simulate the circuitry and operational characteristics of a professional analog recording and mixing desk, with a secondary goal of minimizing physical variables that might influence test results.

The system comprises:

1) A standard 19-inch 4-rack-space aluminum-and-steel housing containing one motherboard and 10 daughter cards (the test circuits), onto which each group of 26 capacitors was soldered. Each test circuit is a two-channel signal path, with 13 capacitors per channel. A single stereo pair of XLR inputs/outputs (I/O) is routed via relays to each of the 10 stereo test circuits.

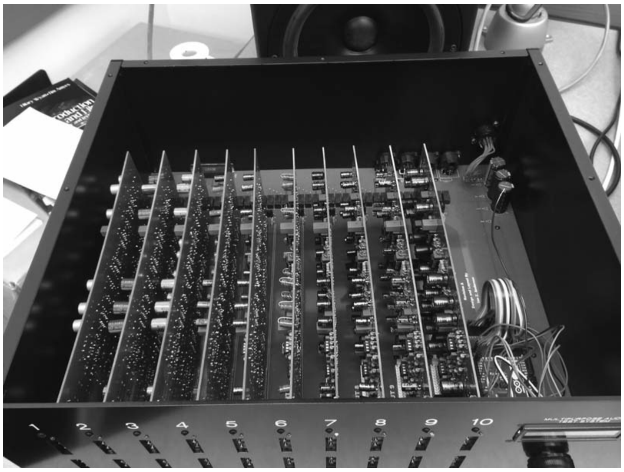

Fig. 1. Test system interior.

This configuration was chosen in an effort to eliminate XLR connectors and cables as variables, while housing all test circuits in the same enclosure will ensure a consistent operating environment for each test circuit.
2) A regulated external linear power supply delivering ±17-V rails to the audio circuitry with a separate 9-V power supply for an Arduino microcontroller and relays.
3) Arduino microcontroller providing both the user interface for the system and control voltages for relay-

Table 3. Rated tan ∂ vs. measured.

Capacitor	*Tan* δ, Rated (Max)	*Tan* δ, Measured Avg.	Standard Deviation
ELNA RFS*	0.10	0.044	**0.0008213**
Lelon REA	0.14	0.040	0.002
Nichicon ES*	0.16	0.034	0.001
Nichicon KZ*	0.12	0.028	0.0013351
Nichicon NS	**0.08**	**0.014**	0.003
Nichicon VZ	0.16	0.106	0.0035554
Panasonic FC	0.14	0.050	0.001
Panasonic FM	0.14	0.032	0.0056861
Panasonic SU	0.15	0.041	0.000997
Vishay/BC ASM	0.14†	0.072	0.004

*denotes capacitors specified for audio use
†Rated @ 100 Hz

Fig. 2. User interface (UI) and precision trimmer potentiometers.

routing the stereo I/O to and from each of the 10 test circuits. A front-panel USB port facilitates programming. Test circuits are selected using a single rotary encoder with an integral momentary push button.

Each audio circuit daughter card comprises two identical line-level analog audio channels with electronically-balanced inputs and outputs. While only one channel of each daughter card was employed during testing for this paper, a two-channel model was selected to facilitate the possibility of future listening tests.

The system's front panel, shown in Fig. 2, contains cutouts to allow access to 25-turn trimmer potentiometers present at each variable gain stage on each daughter card: input trim, channel fader, and master fader.

The system was designed to be flexible and reusable: Future tests on other circuits can be easily executed simply by changing out daughter cards, while the Arduino microcontroller can be reprogrammed to monitor any number of conditions within the housing or individual circuits. Further, the motherboard was also designed to accommodate 8-channel input on a DB-25 connector, routed to the first eight daughter card positions. This will allow for future tests that might require summing to the last two daughter card positions.

1.3.2 The Test Circuits

The test circuit is a direct reproduction of a current-production analog large-format professional mixing desk, from tape/Digital Audio Workstation (DAW) return to mix bus output, including all nonoptional stages in between (i.e., no Equalizer or channel insert send stages were included). The circuit represents the absolute minimum number of amplifier stages in use when monitoring tape/DAW returns or mixing through the desk.

A block diagram of the circuit is shown in Fig. 3.

Each channel of the test circuits consists of 10 operational amplifier stages (packaged within five NE5532APs) with a total of 13 electrolytic capacitors per signal path, each of which functions in a DC-blocking capacity. Three variable gain stages (line input trim, channel fader, and master fader) are controllable via precision multiturn trimmer potentiometers accessible through the front panel, with test points available at each to facilitate precise adjustment and measurement using a multimeter, in this case a BK Precision 2707B.

Note that there are nonpolarized capacitors—in this case, 220 nF polypropylene film/foil WIMA—after the channel and master faders. These were left in place in each test circuit with the exception of an 11th control circuit containing no capacitors.

The reasoning behind this approach to the test circuit design is that a significant number of capacitors per circuit might more effectively represent any cumulative effects of capacitor-induced nonlinearities than a single component subjected to similar tests. In short, the test circuit was designed to simulate a "real world" line-level professional audio circuit of the type employed daily by audio professionals.

A second, simpler test circuit consisting of a single unity-gain inverting op-amp stage with a single 100 uF/25 V DC-blocking capacitor on the input was subjected to THD measurement at +20 dBu only. This test was performed to examine a single capacitor in "higher resolution" outside of the context of a more complicated circuit that might be masking more subtle differences between the tested components.

1.4 Electrical Test and Measurement

Each test circuit was subjected to a battery of audio tests and measurements administered by a Spectral Measurement dScope III. Balanced input and outputs were used, with the dScope's input impedance set to 100 kΩ. Output impedance was set to 50 Ω. The following test battery was performed individually on all 10 test circuits plus an 11th test circuit identical to the other 10, but with all capacitors omitted:

1) THD Sweeps, 20 Hz – 20 kHz (all gain stages set to unity)
   a. +4 dBu
   b. +10 dBu
   c. +20 dBu

2) 31-tone Stimulus
   a. +4 dBu
   b. +10 dBu
   c. +16 dBu
   d. +20 dBu

3) Test circuit 5 randomly selected (Lelon REA), unity gain, with 0.1 μF PET film "bypass" capacitors employed in parallel with all electrolytic capacitors.
4) Test circuit 6 randomly selected (Nichicon MUSE ES), with all NE5532s replaced with LME49720s.
5) THD sweeps, 20 Hz – 20 kHz at +20 dBu on a unity-gain inverting op-amp stage containing a single capacitor at the input.

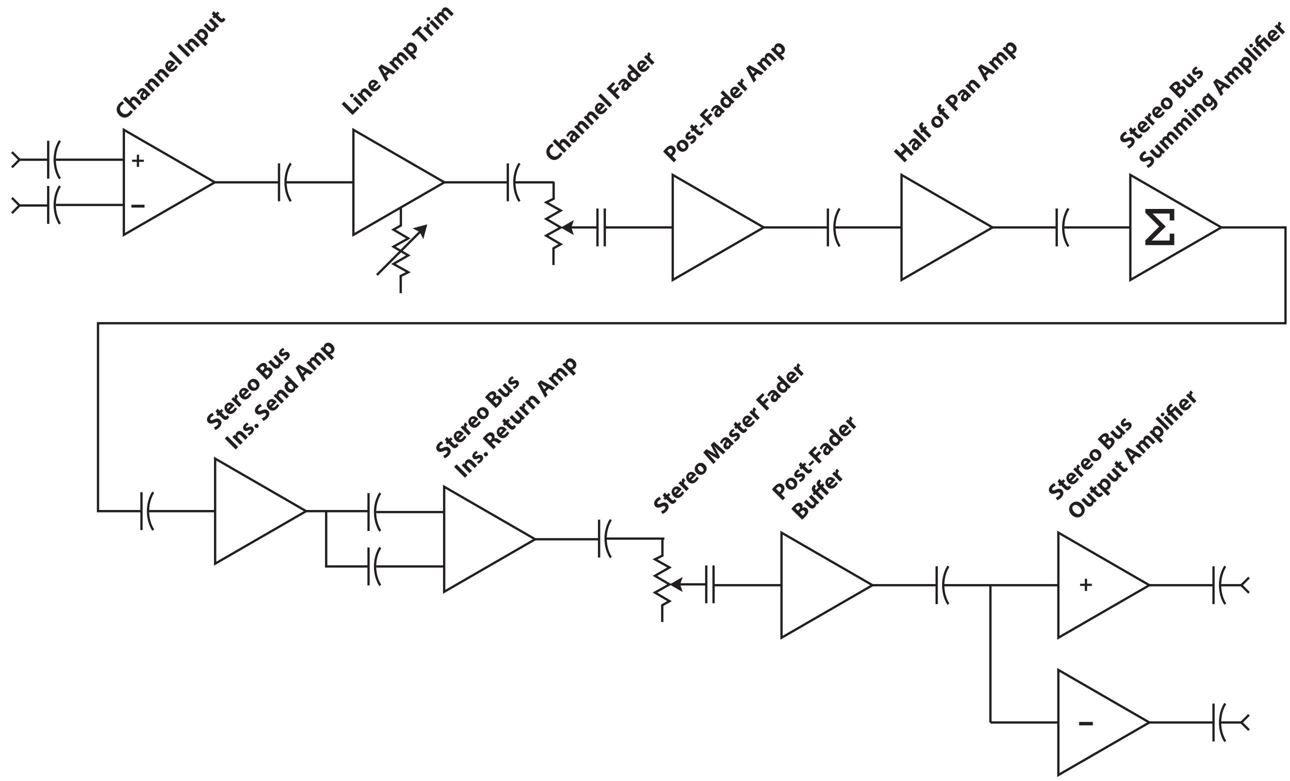

Fig. 3. Test circuit block diagram. One channel shown.

Test 3 is designed to challenge the belief that film-type "bypass capacitors" in parallel with electrolytic types in blocking configuration with minimal DC offset will lower distortion.

Test 4 is another control, utilized in an effort to determine if distortion is dominated by the capacitors or the op-amps.

All THD sweeps are 80-point logarithmic sweeps from 20 Hz to 20 kHz, executed at an internal sample rate of 96 kHz. The dScope's default smoothing transform was applied for readability, averaging 1 point on either side of each acquired point with 2 passes.

Note that these tests are not THD+Noise, but THD, acquired using the dScope's FFT analyzer, eliminating the influence of noise from the results.

2 RESULTS

2.1 THD Sweeps: +4 dBu

The first series of sweeps was performed at +4 dBu with all gain stages at unity gain. Results are shown in Fig. 4.

The bottom trace is the dScope in loopback. The dotted trace second from bottom, visible from 20Hz to 80Hz, is the control circuit without capacitors. Its disappearance into the group of traces representative of circuits containing capacitors already hints that op-amp distortions dominate these measurements, at least at higher frequencies.

The second trace from the bottom (shown solid), visible from 1 kHz to about 15 kHz, is the circuit containing the Nichicon MUSE ES but with all five NE5532s replaced with LME49720s.

The difference in the shape of this curve, which, interestingly, more closely follows that of the dScope, again suggests that op-amp-related distortions shape the distortion characteristic at higher frequencies, while the capacitors provide a bit more influence on the distortion at lower frequencies. Differences between capacitors around 20 Hz are most likely settling-time-related.

Among the 10 capacitor-loaded circuits employing NE5532s, differences appear significant at higher frequencies, at least until one considers the resolution of the image. Indeed, distortions at 20 kHz cover a range of almost exactly 3 dB or 0.00027% (MUSE KZ) to 0.00038% (Panasonic FM, top trace), but this difference is most certainly insignificant when one considers that this is a 3-dB difference in the neighborhood of −110 dB.

For the curious, an examination of the 10 kHz area, where distortion is highest, reveals an even more modest difference of 0.0006%, or about 1.15 dB, between the Panasonic FM and the MUSE KZ.

The spread at 1 kHz is even narrower, at a mere 0.00028% (0.45 dB) between all circuits.

2.2 THD Sweeps: +10 dBu

Results obtained at +10 dBu (Fig. 5) are similar to those obtained at +4 dBu. Increase in distortion across the board is minimal throughout the midrange frequencies and negligible at the lowest. We begin to see a more exaggerated rise in distortion at high frequencies.

At this point, it is worth discussing the obvious difference in the overall shape of the traces in this figure, including that of the dScope loopback trace (bottom, dotted). According

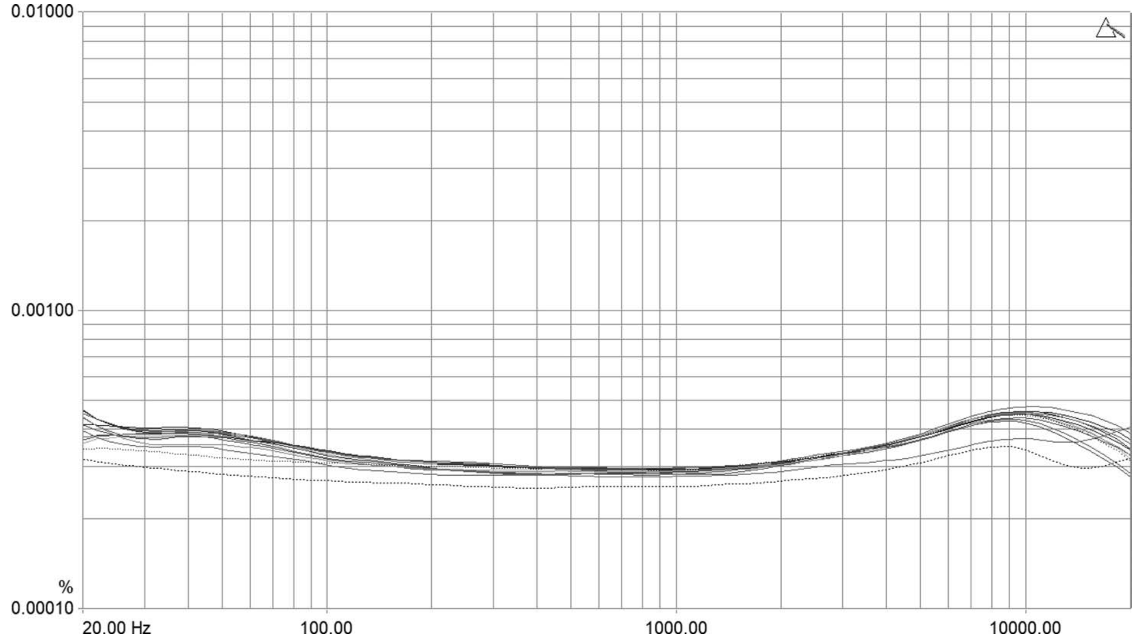

Fig. 4. Total harmonic distortion (THD) sweeps at +4 dBu.

to Spectral, this is a result of the dScope auto-ranging in an effort to achieve the lowest distortion and noise. Curiously, switching off auto-ranging at the dScope's analog inputs yielded no change in the loopback trace.

As for distortion, peak THD in circuits containing capacitors (here, greatest at just under 20 kHz) varies from 0.00056% to 0.00077%, or a difference of about 2 dB. Panasonic FM measures highest again, with the MUSE KZ and Vishay/BC ASM matching the dScope.

Concealed within the group are both the capacitorless control circuit and MUSE ES circuit employing LME49720s. Their presence in the middle of the group, especially that of the control circuit, might raise a few questions, at least until one once again considers the matters of resolution and scale. All of the circuits under test—including the control circuit with no capacitors—are exhibiting traces of distortion only just barely higher than the dScope itself. For all intents and purposes, all test circuits thus far perform as well as the test instrument.

2.3 THD Sweeps: +20 dBu

Results of sweeps at +20 dBu are shown in Fig. 6. Loopback trace is again shown at the bottom, and the Nichicon MUSE ES circuit with LME49720s replacing NE5532APs is shown second from bottom. Immediately noticeable in

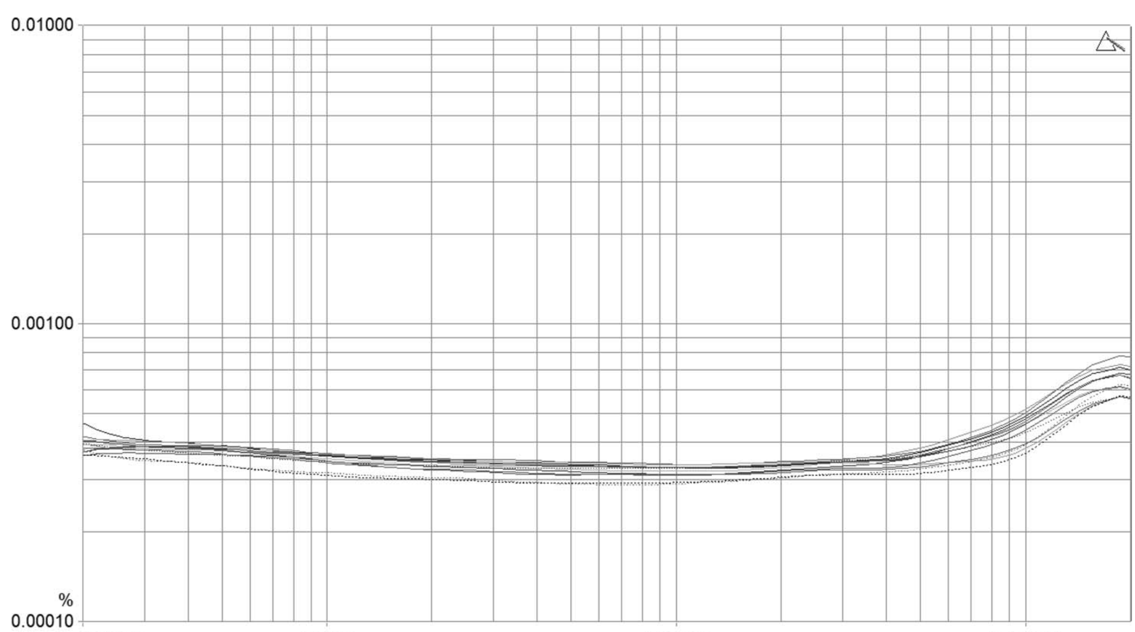

Fig. 5. Total harmonic distortion (THD) sweeps at +10 dBu.

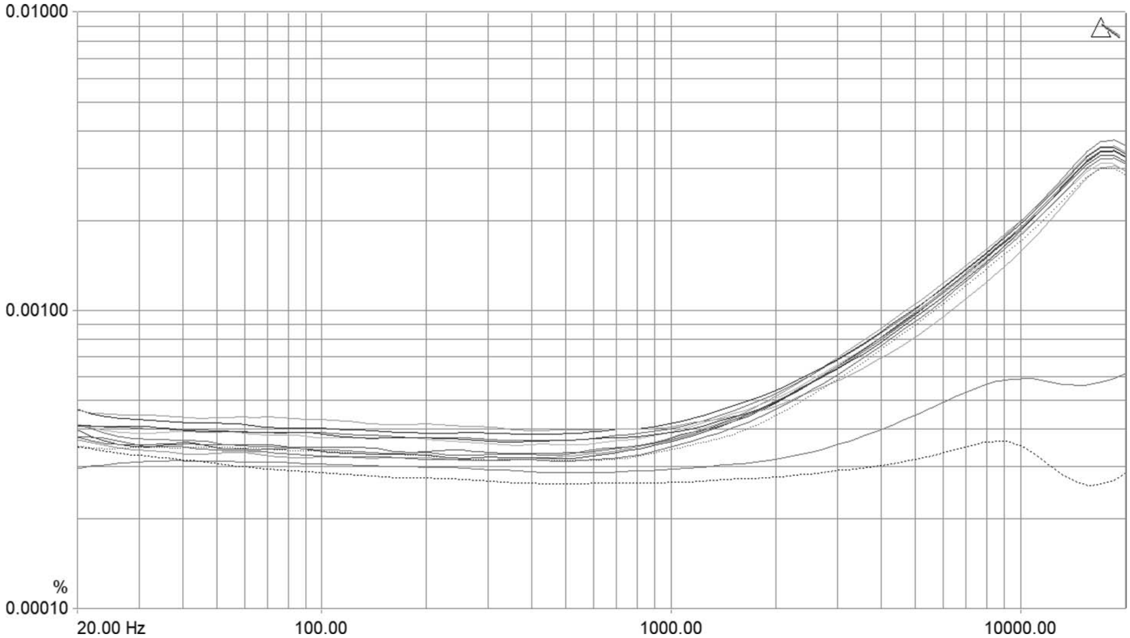

Fig. 6. Total harmonic distortion (THD) sweeps at +20 dBu.

these two traces is a return to the familiar curve present in the +4 dBu traces.

Distortion increases as expected, including—and especially—the common-mode distortions introduced by the operational amplifiers. Any doubt as to the primary source of the distortion in these traces is laid to rest by comparing the cluster to the Nichicon MUSE ES circuit containing LME49720s (solid, second from bottom). The same circuit falls squarely in the middle of the cluster exhibiting higher distortion when the NE5532APs are reinserted.

Distortion present in the 10 original capacitor-laden test circuits again varies only slightly, ranging from approximately 0.0029% (Panasonic FC) to 0.0036% (Panasonic FM), a 1.83-dB difference at around 18 kHz. At 1 kHz, the difference is a bit larger, at 0.00034% (Lelon REA) and 0.00045% (MUSE KZ), a span of 2 dB.

The capacitor-free control circuit (dotted) runs toward the bottom of the pack and is difficult to visually identify, as the Vishay/BC ASM and Panasonic FC "paint over" that trace nearly point-for-point.

Another trace of the Lelon REA circuit, this time with 0.1-μF film "bypass" capacitors in parallel with each electrolytic, nearly perfectly covers up the trace of the Lelon without the bypass capacitors, again suggesting that the inclusion of these extra components yields no improvement in distortion performance.

These results again demonstrate a) that the measurable differences between capacitors in this particular circuit are miniscule, b) that at low frequencies these circuits exhibit distortion comparable to the test instrument, and c) that distortion at high frequencies is dominated by the op-amp.

2.4 THD Sweeps: Single Stage, +20 dBu

Results of THD sweeps on the single-stage, unity gain, inverting op-amp circuits are shown in Fig. 7. It should be noted that FFT settings for this test were carried over from previous tests with one exception: I/O settings were changed from balanced to unbalanced.

It is again immediately noticeable that circuits containing capacitors display slightly higher distortion than the dScope (bottom trace, dashed), and that these traces exhibit the same distortion curve as the THD measurements of the ten-stage circuit at +20 dBu.

The trace for an equivalent circuit containing no input capacitor is shown second from the bottom. Note that, at frequencies above about 1kHz, this circuit is indistinguishable from those containing an input capacitor. Again, at high frequencies and high amplitudes, op-amp distortion dominates.

Also present – and indistinguishable - in the middle of the group is a trace with a WIMA FKP-1 film-and-foil 0.1 μF "bypass" capacitor in parallel with a single Panasonic FC (selected at random). As this trace follows those of the other circuits, it can again be assumed that, in this application, the addition of a film "bypass" capacitor yields no measurable improvement in distortion performance.

2.5 31-Tone Stimulus

THD measurements are at this point well known to be something of a "blunt instrument" in terms of measuring audio performance of a circuit. A multitone test signal is about as close as test and measurement engineers can get to approximating a broadband musical signal from which distortion data can be relatively easily extrapolated. The 31-tone signal employed in this series of tests is a set of logarithmically spaced sine waves of equal amplitude spanning 20 Hz to 20 kHz. Output amplitude of the dScope was normalized, in a series of 4 tests, to +4 dBu, +10 dBu, +16 dBu, and +20 dBu.

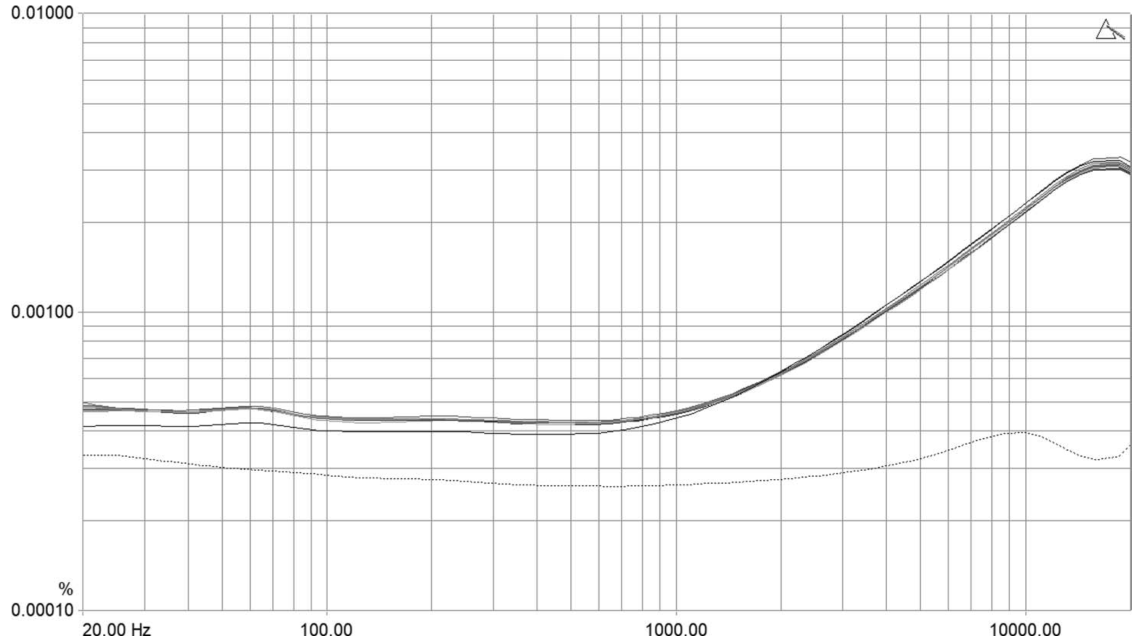

Fig. 7. Total harmonic distortion (THD) sweeps, single-stage unity gain inverting amplifier, +20 dBu.

+16 dBu is the point at which the control circuit displays approximately 1% distortion, while the +20 dBu stimulus is intended to facilitate examination of distortion products with the test circuits under extreme duress.

The resulting measurement, Total Distortion, is a product of all harmonic and intermodulation distortions introduced by the 31 tones and is given as a percentage of the total signal. Total distortion measurements for all capacitors at +4 dBu, +10 dBu, +16 dBu, and +20 dBu are shown in Table 4. All results are averaged from eight acquisitions and rounded to three decimal places.

Results of all tests at +4 dBu and +10 dBu show no appreciable increase in distortion products over the test instrument. At +16 dBu, we begin to see slight differences between capacitors, but still no more than a 0.25% increase in distortion over the control.

The Nichicon NS circuit appears to measure better than the control, though this is most likely a result of minute differences in gain between the two circuits in conjunction with the resolution limits of the test instrument.

A noticeable increase in total distortion between the control circuit and all circuits containing capacitors isn't seen until +20 dBu. The tremendous amount of distortion present at this signal level is, naturally, a result of extreme clipping, as it is present even in the capacitorless control circuit. This test was performed primarily as an experiment in resolution: how significantly different are the capacitors' distortion products at extremely—and admittedly uselessly—high signal levels?

While total distortion is indeed significantly greater in the circuits containing capacitors, the difference between lowest and greatest distortion measurements (1.5% between the Nichicon MUSE ES and the Nichicon MUSE KZ, respectively) is, again, minimal.

At all signal levels the presence of 0.1-uF film "bypass" capacitors made no improvement in the distortion performance of the Lelon REA capacitor, the least-expensive

Table 4. Total distortion (TD) results, 31-tone stimulus.

Capacitor	TD% at +4 dBu	TD% at +10 dBu	TD% at +16 dBu	TD% at +20 dBu
Nichicon NS	0.004	0.004	1.008	49.298
ELNA Silmic II*	0.003	0.004	1.157	49.451
Nichicon MUSE ES	0.003	0.004	1.082	49.962
Lelon REA	0.004	0.004	1.227	49.732
Panasonic FC	0.004	0.004	1.196	49.104
Vishay/BC Comp. ASM	0.004	0.004	1.017	48.878
Panasonic SU	0.003	0.004	1.013	49.061
Panasonic FM	0.004	0.005	1.167	49.355
Nichicon VZ	0.003	0.004	1.037	48.933
Nichicon MUSE KZ*	0.003	0.004	1.024	48.435
Control - No Capacitors	0.003	0.003	1.010	41.035
Lelon REA "Bypassed"	0.004	0.004	1.262	49.808
dScope Loopback	0.004	0.003	0.003	0.004

*denotes capacitors specified for audio use capacitor tested here. In fact, at +16 dBu and +20 dBu, the Lelon REA circuit containing bypass capacitors tested slightly worse than the circuit without.

3 SUMMARY AND DISCUSSION

This series of tests demonstrates that, in line-level applications designed around operational amplifiers where DC offset is minimal, differences in measurable distortion products between a variety of electrolytic capacitors—including expensive parts designated as "audio grade"—are negligible and, in most cases, approximate the residual of the test instrument.

Further, the addition of so-called "bypass" film capacitors in parallel with each electrolytic capacitor are, at least in this application, a pointless supplement.

Finally, these test results demonstrate that the choice of op-amp will have a more significant impact on the overall distortion characteristic than the choice of DC-blocking capacitors.

Ultimately, these results suggest that audio electronics designers developing line-level circuits around operational amplifiers in which DC offset voltages are minimal would be best served choosing capacitors that offer a balance between cost and long-term durability, rather than unmeasurable claims of superior audio performance.

Prior work suggests that further testing on circuits employing a single-ended power supply—in which much higher DC bias voltages will be present—might yield different results, though such circuits are not representative of contemporary line-level audio circuit design around operational amplifiers. Then again, given the renewed interest in discrete transistor designs from the 1960s and 1970s, results of such tests might be of interest to designers. It would be relatively easy to develop circuits for this test system that operate on a single-ended, higher-voltage power supply and acquire more data.

Additional testing on circuits with AC voltages across each capacitor—for example, in filter or equalizer circuits (with electrolytic capacitors in shunt configuration) set "flat"—might also yield different results.

The author also suspects that the tests presented in this paper will do little to assuage subjectivists who will almost certainly continue to insist that one brand of capacitor sounds different from another in this particular application; a carefully constructed listening test will almost certainly be the only way to truly lay the issue to rest.

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