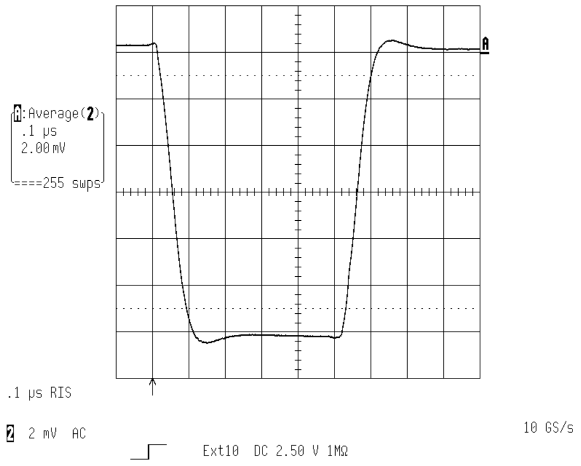
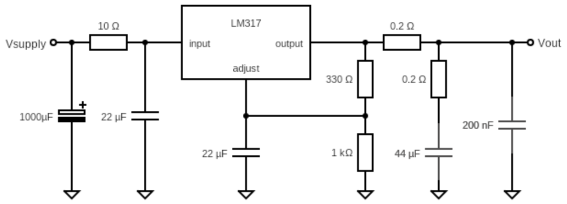
Successfully team up elderly regulators with youthful capacitors

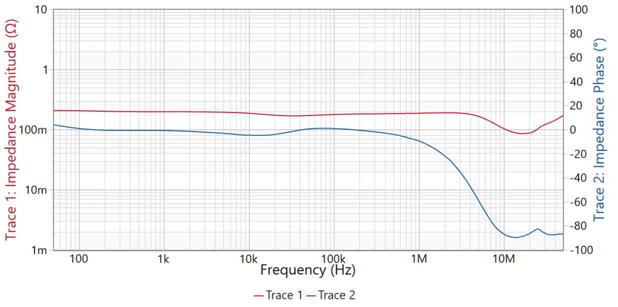
Or what a flat impedance can do for you

Summary

This white paper shows the measurements and methods to characterize the output impedance of a LM317 linear regulator setup using an Omicron Lab Bode 100. With the gathered information, a suitable output capacitance and ESR value are derived to achieve a non-peaking impedance curve. A circuit tweak is shown to replace the required ESR by external resistors to optimize the impedance curves even further without disturbing the regulator control loop. A flat output impedance is achieved by only using cost effective MLCC technology.







Why the ancient LM317?

The infamous LM317 was introduced by National Semiconductor in 1976 and is therefore one of the oldest integrated voltage regulators still used today. For usage in bipolar power supplies, a complementary negative voltage regulator LM337, designed by Bob Pease himself, is available. Due to its adjustable output voltage and a reasonably high input voltage tolerance, this set of regulators is still a popular choice among worldwide analog circuit designers.

However, the LM317 was never designed to work with strictly capacitive output loads, which is true for many other regulators on the market. Yet high speed circuits often require local load decoupling which is usually done with MLCCs close to the supplied ICs, asking the regulator to do exactly that: To work with a capacitive load and ideally have a minimal load step response without ringing.

If even an elderly regulator like the LM317 can be paired with these youthful capacitors to achieve outstanding results, it raises expectations towards the last 50 years of regulator development and what can be achieved using the same methodology.

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Meet the test and measurement setup

In this work, the LM317 regulator is used to create a 5.0 V voltage output at 9.0 V supply voltage. To pre-filter the input voltage, a 10 Ω resistor in combination with a 22 µF MLCC decoupling capacitor should dampen any supply noise beyond ~800 Hz. The local feedback for the LM317 consists of a voltage divider 330 Ω over 1 kΩ, which in combination with the adjust pin bias current results in a nominal output voltage of 4.97 V. The impedance measurement is happening on the port Vout.

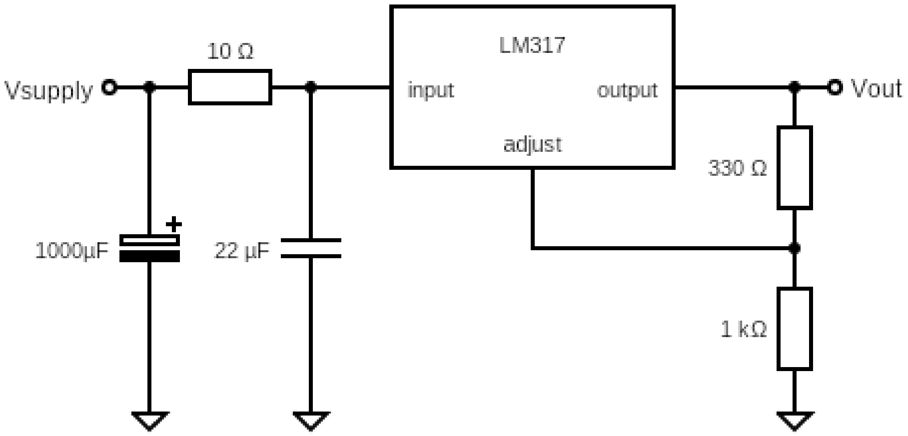
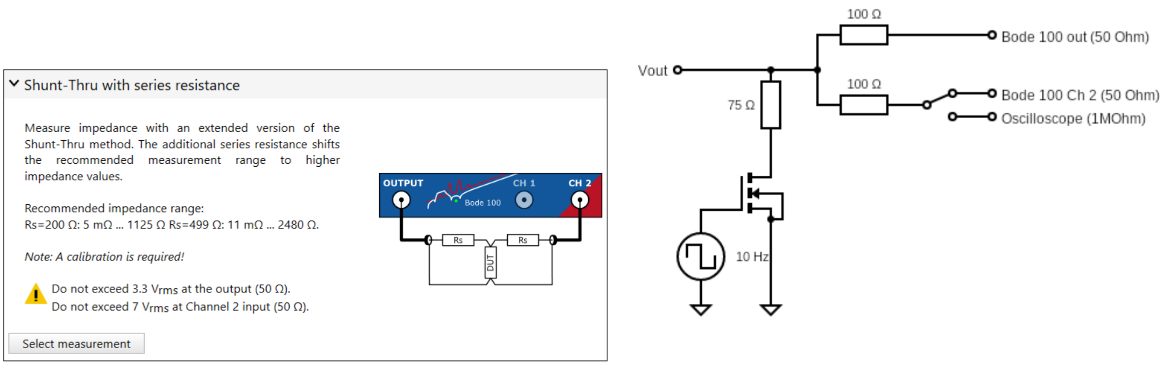


Figure 1 - Circuit under test with connection ports and baseline circuitry

The ideal measurement setup to measure the expected low output impedance of the system with the Bode 100 would be the Shunt-Thru 2-port measurement. As the output DC voltage of 5 V exceeds the recommended max. voltage of 3.3 V_{rms} for the Bode 100 output, the solution is to set up for the “Shunt-Thru with series resistance” setup and add Rs = 100 Ω resistors. This increases the acceptable DUT voltage to 10 V_{rms} and imposes an external resistance of (100 + 50) Ω / 2 = 75 Ω on the DUT output. This loads the LM317 with an output current of $I_{load} = \frac{4.97\,V}{75\,\Omega\,||\,1.33\,\text{k}\Omega} = 70\,mA.$ For convenience, the required Rs resistors have been added to the test PCB, but could also be connected externally in form of BNC series attenuators or for highest versatility by using a Picotest P2102A 2-Port Probe. Additionally, a common mode Choke has been placed in the connection to Port 2 of the Bode 100 to improve the accuracy of the measurements.


Shunt-Thru with series resistance

Measure impedance with an extended version of the Shunt-Thru method. The additional series resistance shifts the recommended measurement range to higher impedance values.

Recommended impedance range:
Rs=200 Ω: 5 mΩ ... 1125 Ω Rs=499 Ω: 11 mΩ ... 2480 Ω.

Note: A calibration is required!

Do not exceed 3.3 V_{rms} at the output (50 Ω).
Do not exceed 7 V_{rms} at Channel 2 input (50 Ω).

Figure 2 – Bode Analyzer Suite Measurement setup and DUT connection

Further, for each measurement a load step measurement is performed, and the resulting voltage response is monitored with an oscilloscope. For this measurement, Channel 2 of the Bode 100 is disconnected and the high-impedance oscilloscope input connected instead, which reduces the idle load current to $I_{off} = \frac{4.97\,V}{150\,\Omega\,||\,1.33\,\mathrm{k\Omega}} = 37\,mA$. By periodically enabling a transistor with an additional 75 Ω series resistor, a load current of $I_{on} = \frac{4.97\,V}{75\,\Omega\,||150\,\Omega\,||\,1.33\,\mathrm{k\Omega}} = 103\,mA$ is drawn, resulting in a load step of I_{step} = 66 mA.

Setting a baseline

According to the data sheet, while the LM317 does not require an output capacitor for stable operation, an input capacitor is recommended. Figure 1 shows this configuration with an input capacitor of C_{in} = 22 µF. When measuring the output impedance of this system, as shown in Figure 3, while the low frequency impedance is less than 100 mΩ below 5kHz, it is dominated by an inductive rise with Ls = 3.7 µH at 20 kHz and exceeds 10 Ω in magnitude towards higher frequencies.

The load step response, as can be seen the top right box, shows excursions of roughly 0.5 V and a dominant high pass characteristic as is expected from the impedance.

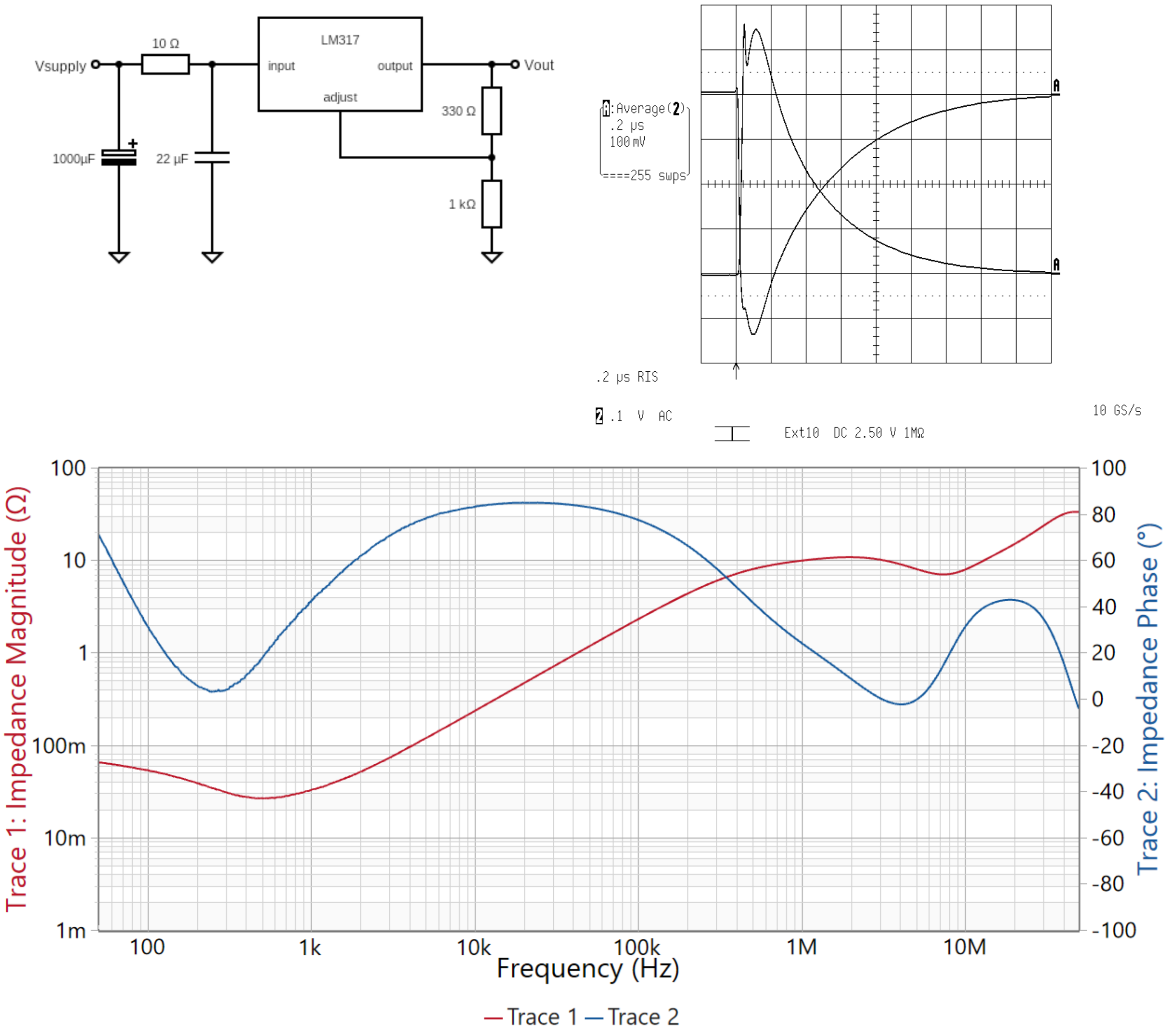


Figure 3 – Impedance over frequency of the baseline circuit

Adding load capacitance

When adding a load capacitor of C = 100 nF, the output impedance of the system becomes capacitive over ~260 kHz, yet a resonance peak forms at that frequency as can be seen in Figure 4. While the excursion in the load step response has reduced to less than 300 mV, it also shows ringing that could lead to the formation of rogue waves.

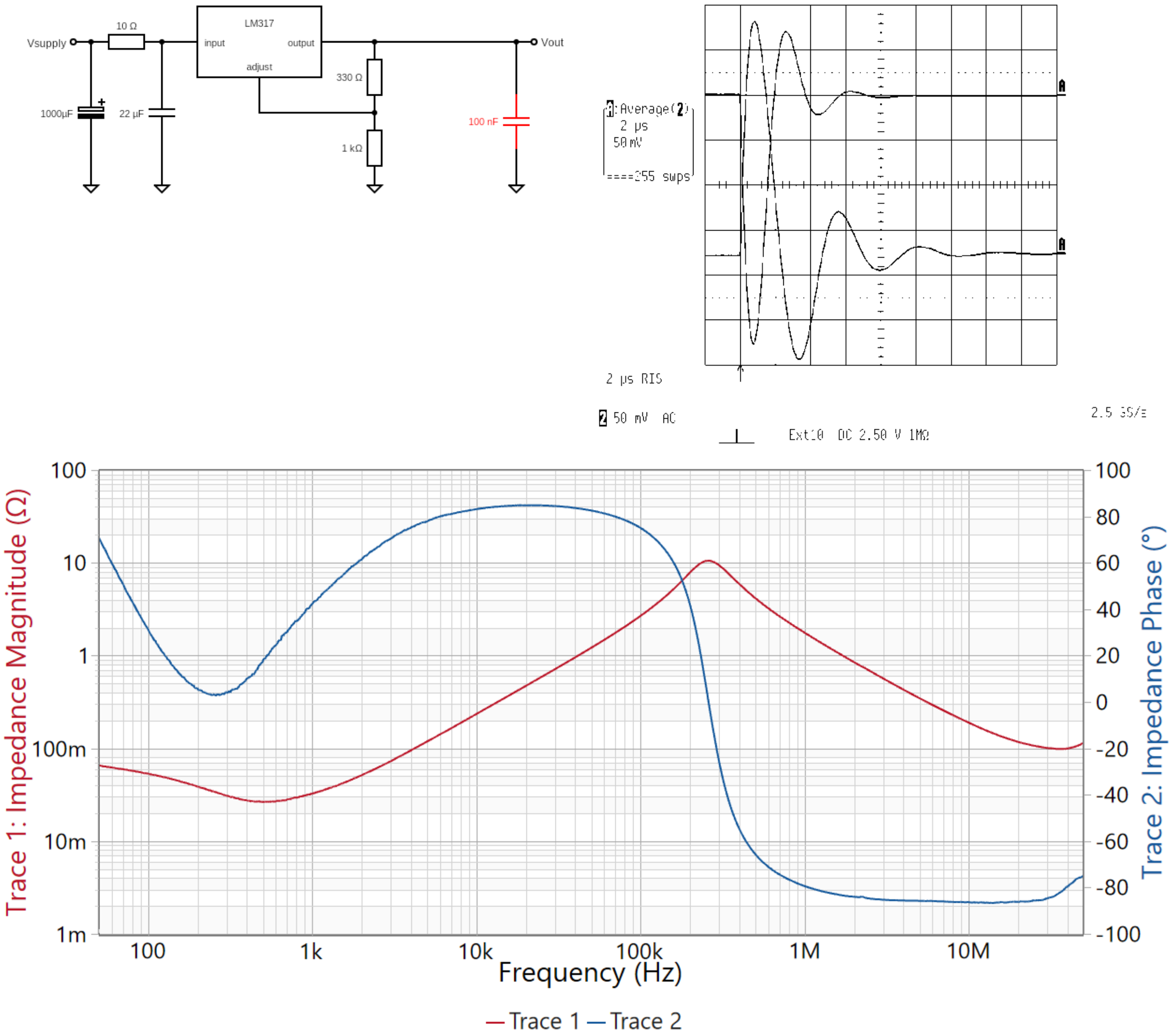


Figure 4 – C_{in} = 22 µF, C_O = 100 nF

Improving the regulator loop with a bypass capacitor

The inductive behavior of the regulator stems from the decreasing control loop gain over frequency, which means that by improving the regulators control loop gain or bandwidth should result in a lower output impedance over a larger frequency band. This is why a bypass capacitor from the LM317 adj pin to GND is recommended, shorting the adj pin to GND for AC signals. The effect of adding C_{adj} = 22 µF to the circuit is shown in Figure 5.

Now the impedance stays below 100 mΩ up to 17 kHz with a readout of Ls = 925 nH at that frequency. The single resonance shifts up in frequency to 580 kHz and limits the impedance magnitude to 3.5 Ω. The load step response shows an excursion of ~120 mV with a dampened, but still noticeable ringing at a now higher frequency.

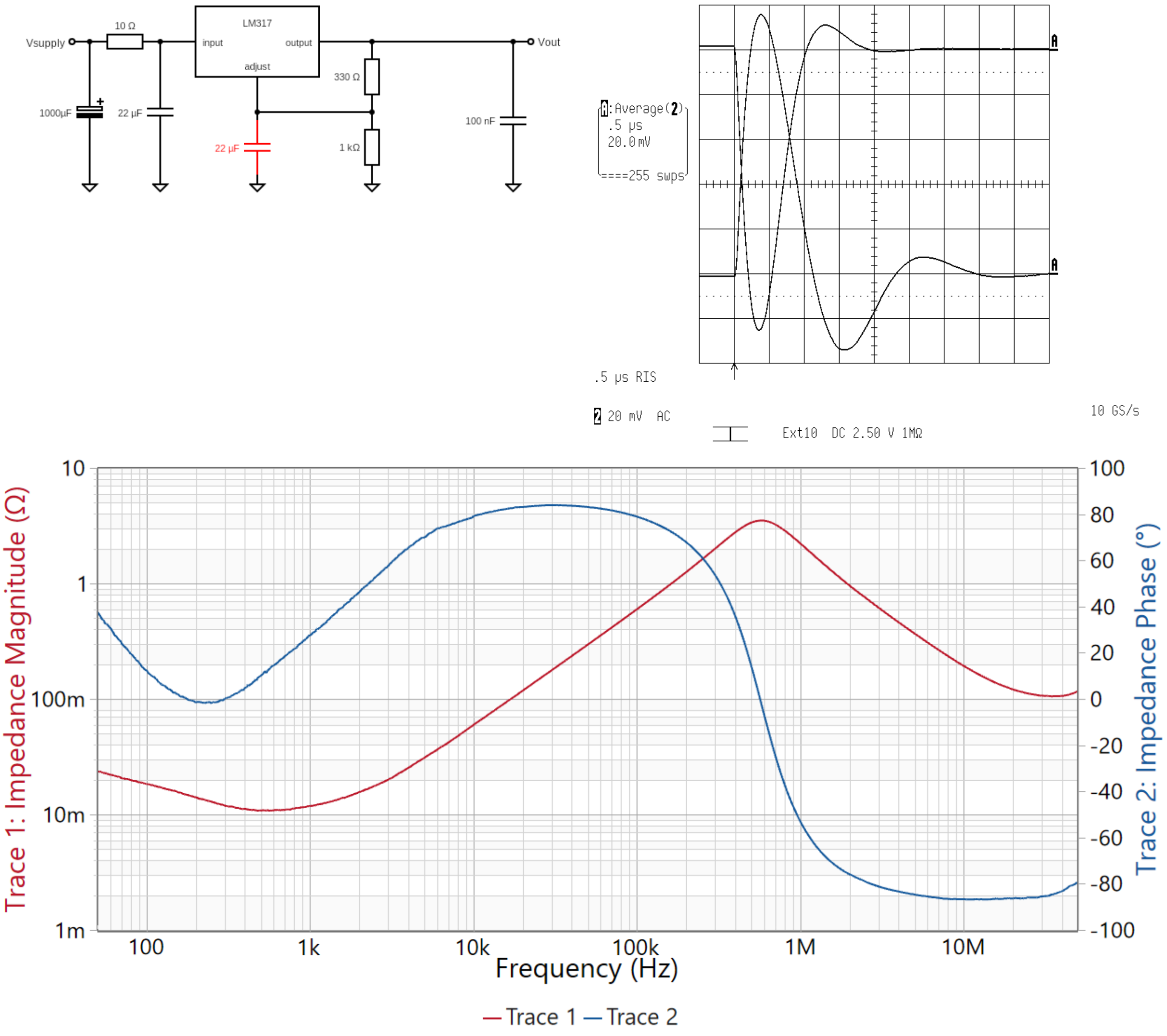


Figure 5 – C_{in} = 22 µF, C_{adj} = 22 µF C_O = 100 nF

Lowering the mid-frequency response by introducing a buffer capacitor

Introducing a 22 µF output capacitor, the regulators inductive output impedance and the capacitances impedance should meet at ~35 kHz and a magnitude of ~205 mΩ, but instead Figure 6 shows two distinct resonances in the impedance plot. From the measurement, the introduced capacitance can be extracted as Cs = 13.8 µF, which is likely caused by the voltage bias over the X7R dielectric, and results in a resonance peak at 39 kHz with a magnitude of 1.3 Ω. The second peak is formed at ~8 MHz where the ESL of the introduced 1210 MLCC capacitor and the load decoupling 100 nF 0603 MLCC capacitor meet. While this is an improvement in reducing the maximum impedance, the load step response now shows significant ringing at the two distinct frequencies with excursions of up to 15 mV.

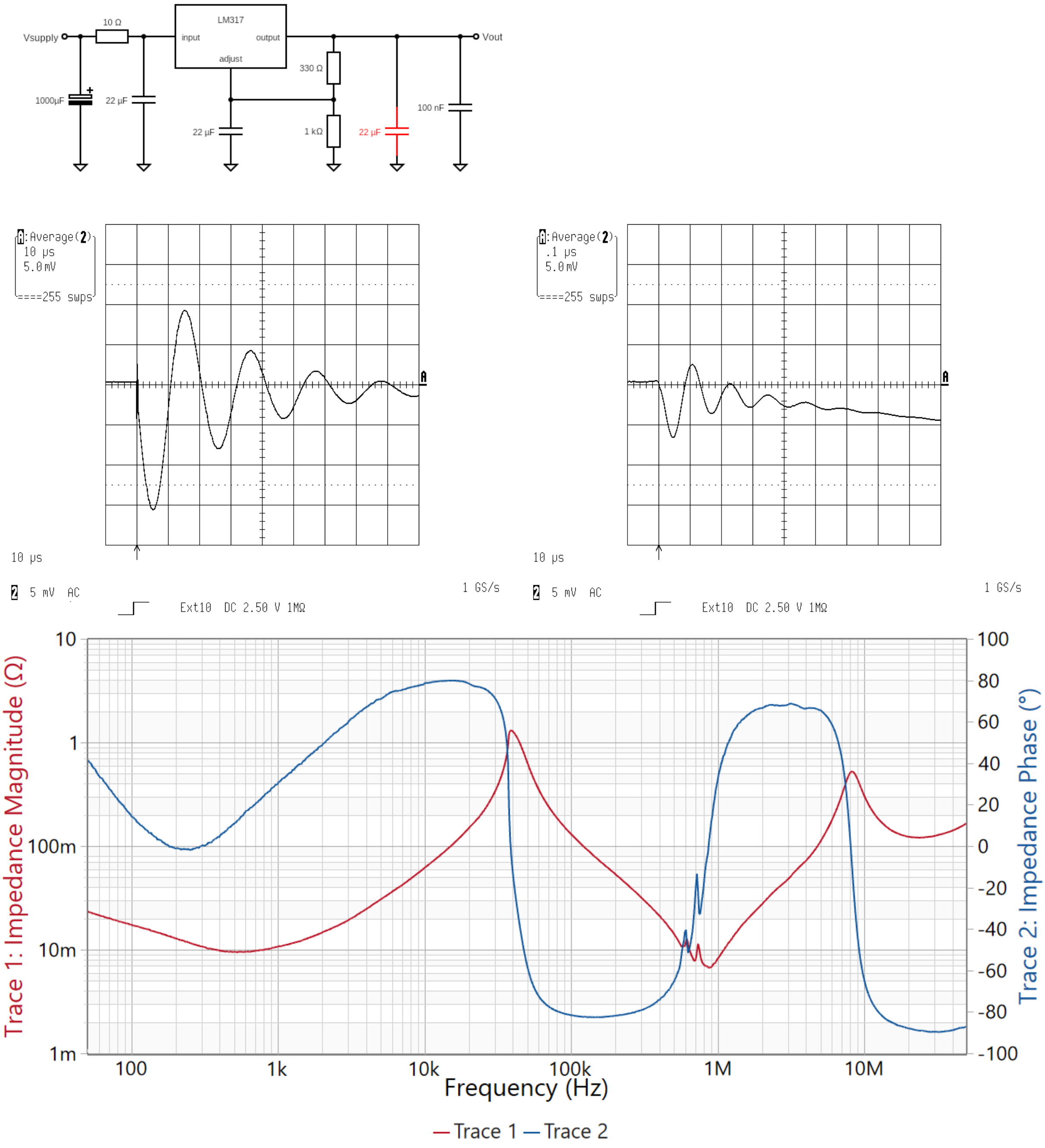


Figure 6 – C_{in} = 22 µF, C_{adj} = 22 µF C_O = 22.1 µF

Dampening the output resonance – the classical way

A series resonator, as is formed between the inductive regulator output and C_{out}, can be dampened by introducing a series R to the circuit, so that $R = \frac{1}{Q}\sqrt{\frac{L}{C}}$, where $Q \leq 0.5$ for overdamping. The simplest and most used way to introduce this series R is to use the intrinsic ESR of an electrolytic capacitor. Those come at the cost of ageing effects and large footprints, whereas more recent capacitor technologies such as tantalum polymer capacitors solve these issues at the cost of a much higher retail price. So, a cost-effective way to get a distinctive ESR value and a small component footprint is to keep using MLCCs with an external low ohmic series resistor.

To critically dampen a series resonance with L = 925 nH and C = 22 µF a resistor of R = 410 mΩ would be optimal, and due to the established lower value of the circuits C_{out} this should more than suffice to result in a non-peaking behavior.

Figure 7 shows this setup with a 400 mΩ ESR. In the frequency plot now the lack of resonance peaks is noticeable. Both the inductive output impedance of the regulator and the load decoupling 100 nF MLCC see the resistive 400 mΩ impedance, forming non-resonant corners. As now the dominant behavior of the output circuitry is that of an R-L high pass filter with ~51 kHz corner frequency, which can also be observed in the load step response with a peak excursion of ~25 mV and no ringing as expected.

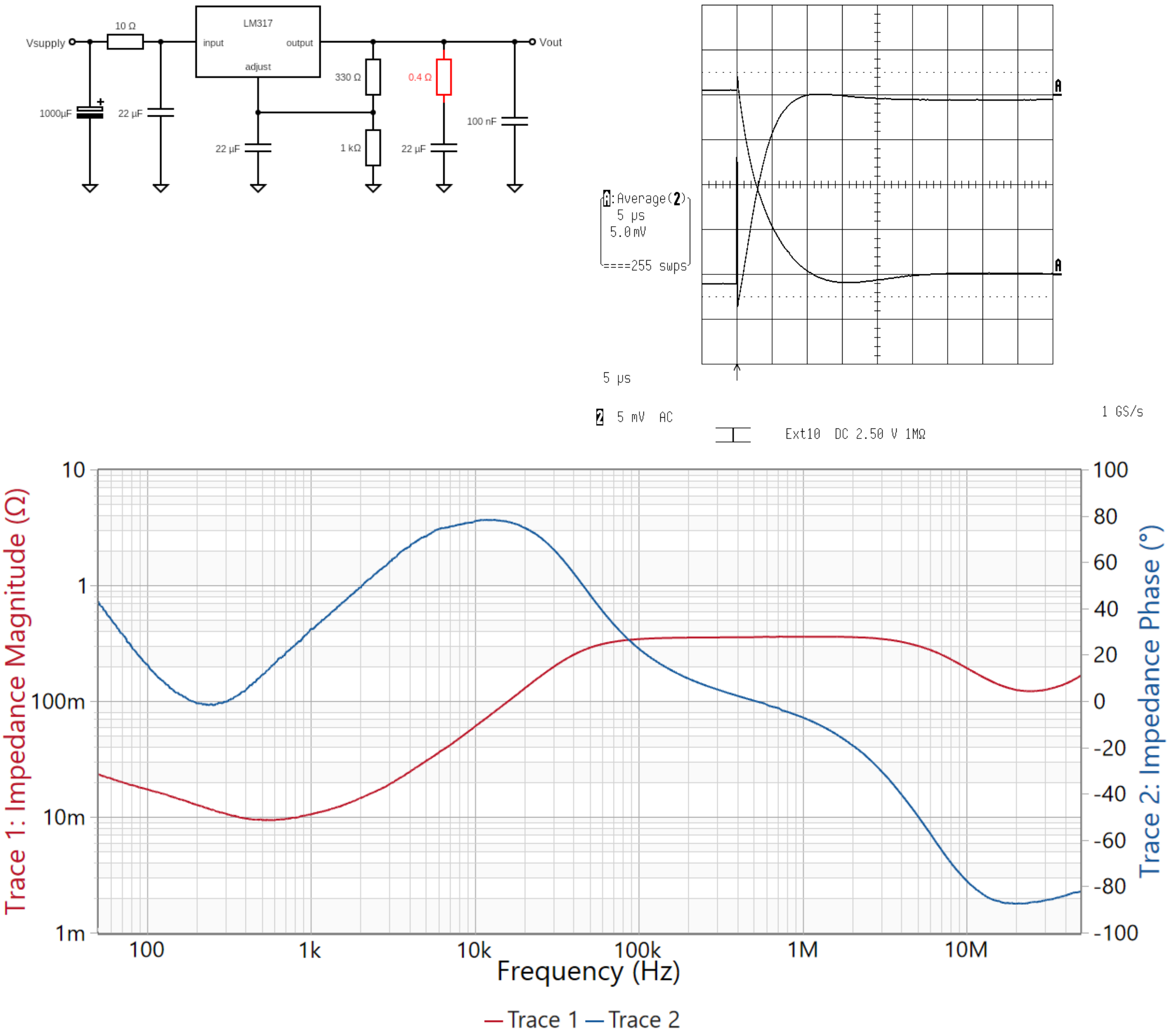


Figure 7 – Cin = 22 µF, Cadj = 22 µF, CO = 22.1 µF, ESR = 400 mΩ

Distributing the dampening – the modern way

To critically dampen the L-C resonance at the output of the regulator, the series R = 400 mΩ can be distributed between the regulator output and the MLCC series path, allowing for the load connected to V_{out} to "see" a much smaller output impedance. When splitting the 400 mΩ ESR resistance into two separate resistors, the resulting circuit with ESR = 200 mΩ and Rs = 200 mΩ is shown in Figure 8.

The side effect of adding a resistor to the regulator output is that the impedance at low frequencies is no longer determined by the regulators' control loop gain. The impedance is reasonably flat around the expected 200 mΩ value, yet now there are visible peaks at ~40kHz and ~7 MHz, where the L and C in series with their respective R component increase the overall impedance.

As now the DC impedance is increased, the load step response does not return to the initial voltage but remains elevated. The voltage settles at around 13.5 mV from the load step of I_{step} = 66 mA, which verifies the 200 mΩ target, yet the excursion peaks at ~16.5 mV.

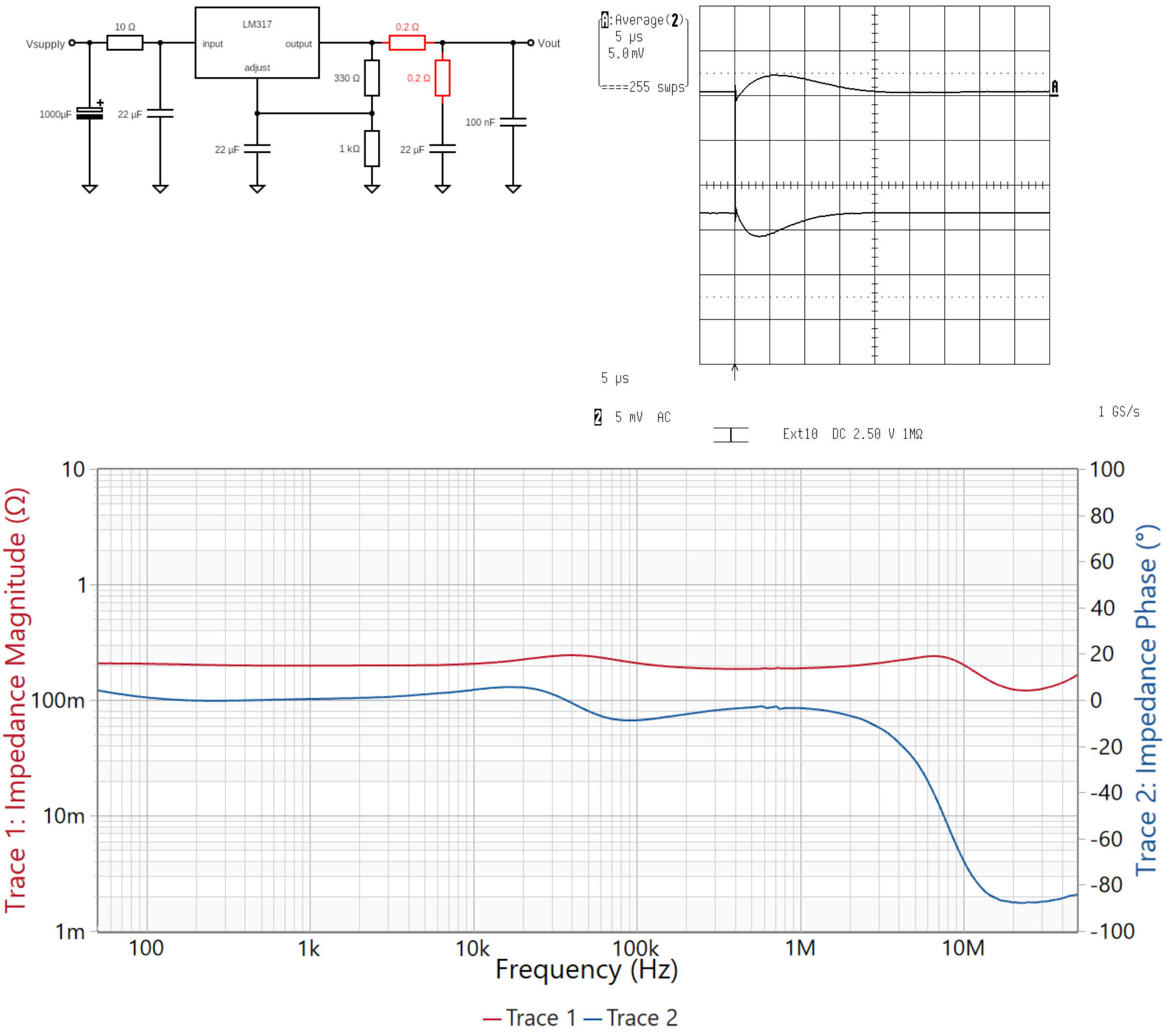


Figure 8 – C_{in} = 22 µF, C_{adj} = 22 µF, C_O = 22.1 µF, ESR = 200 mΩ, Rs = 200 mΩ

Flattening the curve – the goal

To decrease the remaining impact of the regulator control loop or the output capacitance on the overall impedance that the load sees, each of the initial resonances can be shifted towards lower frequencies by increasing their respective C components. In case of the test circuit, C_{out} = 44 µF was chosen to double the value and the decoupling capacitor at the load was selected so that C_L = 220 nF.

The circuit and its respective measurements in this configuration are shown in Figure 9. The impedance now consists of a near linear resistance of 200 mΩ up to ~3.8 MHz, which fits the calculated value for the RC corner frequency of $f = \frac{1}{2\times\pi\times220\,nF\times200\,m\Omega} = 3.6\,MHz$. Within the 50 MHz measurement range of the Bode 100, the impedance stays at or below 200 mΩ.

As can be seen from the step response, which in this case is demonstrated with a complete pulse, the voltage settles within 200 ns to ~13 mV and shows a negligible excursion. The edge shape is dominated by the high frequency response of the used decoupling MLCC and shows no ringing.

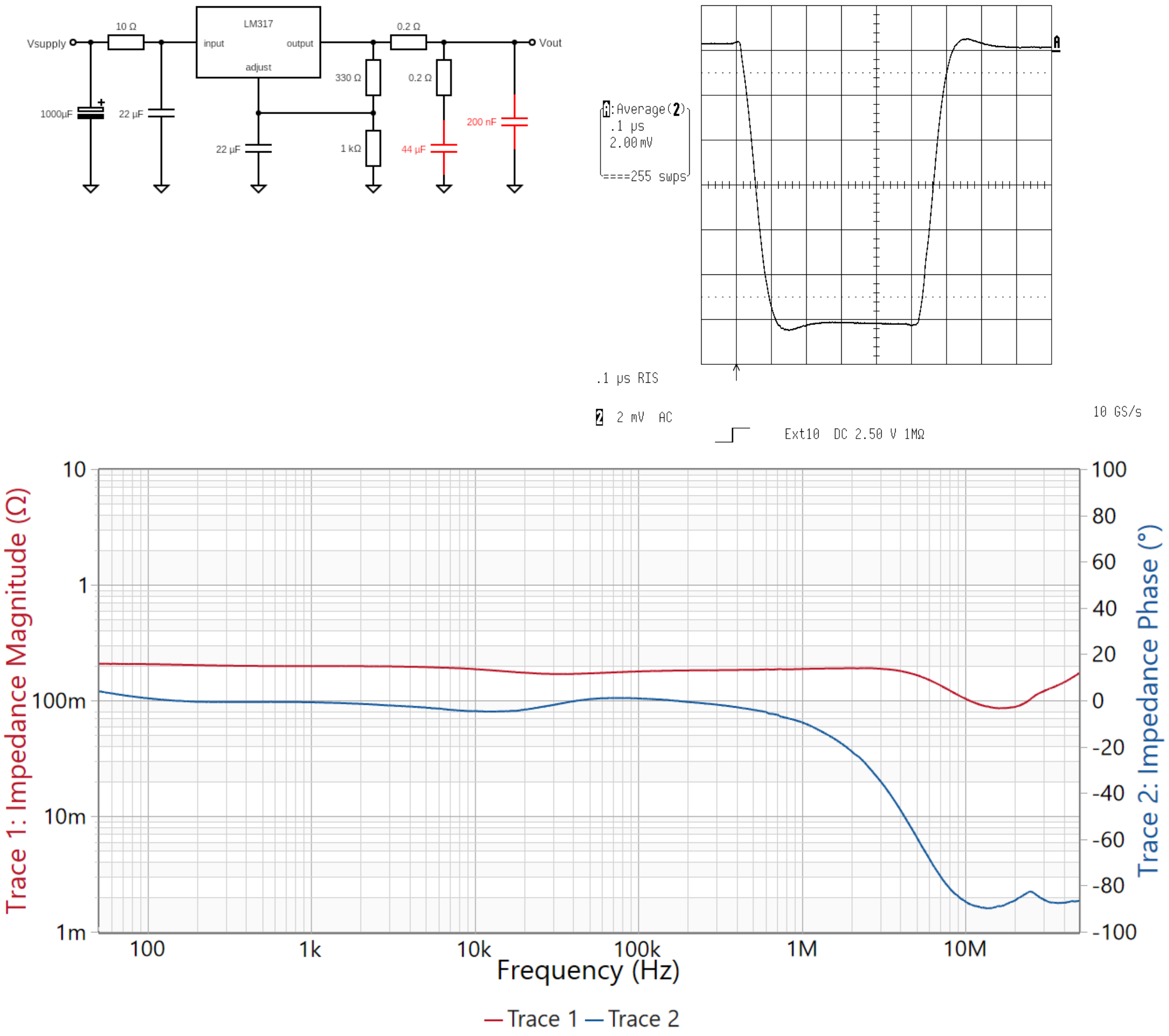


Figure 9 – C_{in} = 22 µF, C_{adj} = 22 µF, C_O = 44.22 µF, ESR = 200 mΩ, Rs = 200 mΩ

Conclusion

Voltage regulators like the LM317 were not designed for ultra-low impedance power supplies as can be achieved with modern MLCCs. To understand the inductive behavior of a given regulator, the output impedance of the circuit can be measured using a Bode 100 with limited external components. The circuit can then be optimized to achieve a very low near-resistive impedance in a broad frequency range. Even though such results may be achieved using Aluminum-polymer electrolytic capacitors or tantalum-polymer capacitors, MLCCs with external SMD resistors not only provide lower costs and smaller overall footprints but also make it possible to optimize the full frequency response.

The shown optimization method can be scaled for lower impedance goals by introducing higher capacitance values and thereby reducing the necessary dampening resistance.

No change in the regulators control loop is required for this optimization method, so once the output impedance can be measured, elderly voltage regulators paired with youthful capacitors can make a great racing team.