

Understanding DC and AC Load Diagnostics in Automotive Class-D Amplifiers

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ABSTRACT

Load diagnostic technologies are widely used in automotive audio applications today. TI's latest automotive class-D audio amplifiers have integrated both DC and AC diagnostics to meet the various automotive audio system diagnostic requirements. This application note introduces the concept of DC and AC diagnostics and their working principles. Two special cases, back EMF handling and using DC diagnostics on AC coupled speakers, are covered.

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1 Introduction

In modern automotive audio systems, multi-speaker structures are quite common. As [Figure 1](#) shows, a typical automotive audio system is a two-way system consisting of a woofer in parallel with a tweeter. The woofer is DC coupled for the low-frequency range and the tweeter is AC coupled via a series capacitor for the high-frequency range. To meet the diagnostic requirement for both speakers, load diagnostics are further split into two subsections, DC and AC diagnostics. DC diagnostics quickly check if there is an open or short connection on the output, while AC diagnostics measure characteristics of the AC coupled tweeter and identify if it has a normal connection.

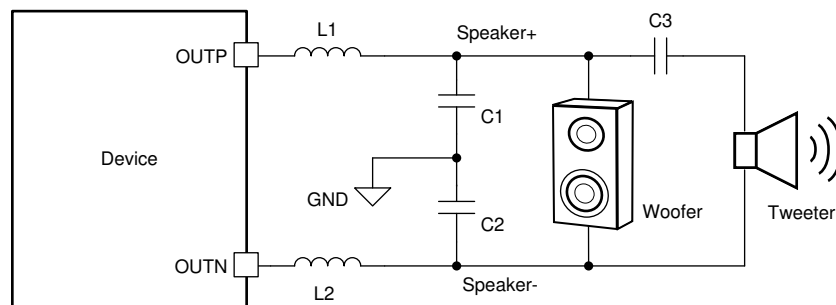


Figure 1. Typical Two-way System in Automotive Audio Application

TI's automotive Class-D audio amplifiers – TAS642x-Q1 series (TPA6404-Q1 and TPA6304-Q1) offer a complete solution for both DC and AC diagnostics. This application note gives an insight into the working principle of DC and AC diagnostics. Additionally, special cases, like back EMF handling and running a DC diagnostic of an AC coupled tweeter are also discussed.

2 DC Diagnostics

2.1 What is DC diagnostics

DC diagnostics focuses on incorrect connections from amplifier to speaker and the speaker itself. It reports fault details and protects the audio amplifier and the speaker from delivering a mass of energy into a potentially unsafe load, which may lead to damage. DC diagnostics tests for the following items:

- Short to Power (S2P)
- Short to Ground (S2G)
- Shorted Load (SL)
- Open Load (OL)

[Figure 2](#) shows the simplified diagram of the configuration between the audio amplifier output stage and the speaker.

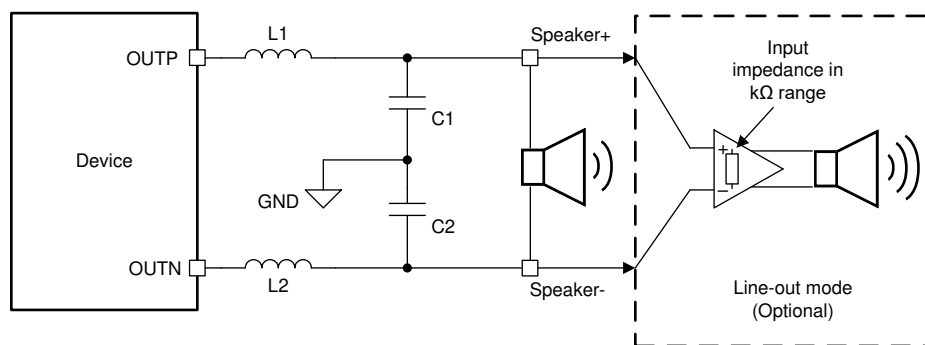


Figure 2. Typical Configurations Between Audio Amplifier and Speaker

Short to Power and Short to Ground detects if the output pins (OUTP/N) or speaker terminals (speaker±) are shorted to the battery or GND. Shorted Load (SL) and Open Load (OL) measures DC resistance between OUTP/N to check if it is shorted or open.

DC diagnostics has an additional mode called *Line Out* mode. The *Line Out* feature allows the Class-D audio amplifier output capable of driving other external audio amplifiers, which usually have a high-input impedance in kΩ range. In DC diagnostics, if the *Line Out* mode is selected by the register settings, the resistance threshold will be changed to a higher value for open load detection.

2.2 Working Principle

2.2.1 S2P and S2G

Figure 3 shows the simplified block diagram of DC diagnostics circuitry for S2P and S2G.

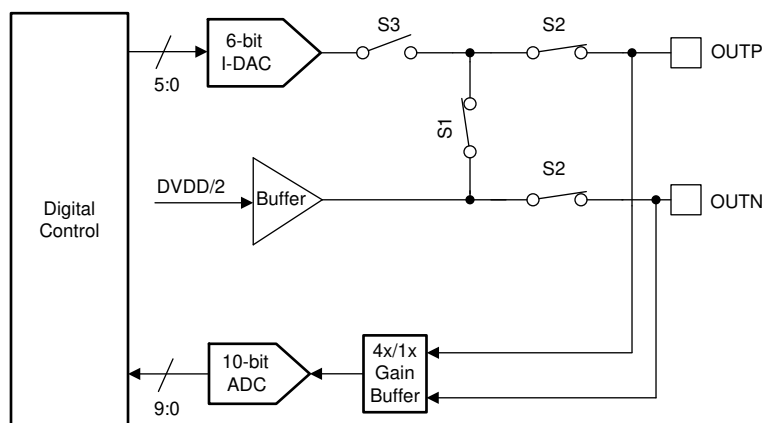


Figure 3. Simplified Block Diagram of S2P and S2G Diagnostics Circuitry

For S2P and S2G diagnostics, S1 and S2 are closed, S3 is opened. The buffer is connected to weakly bias both OUTP and OUTN through S1 and S2 to $\frac{1}{2}$ the DVDD voltage. An internal 10-bit ADC measures the voltage on the OUTP/N pin. The results are compared with the preset thresholds. If any voltage exceeds the upper threshold, a S2P fault will be identified. Likewise, a S2G fault will be identified if any voltage is below the lower threshold.

2.2.2 SL and OL

Figure 4 shows the simplified block diagram of DC diagnostics circuitry for SL and OL.

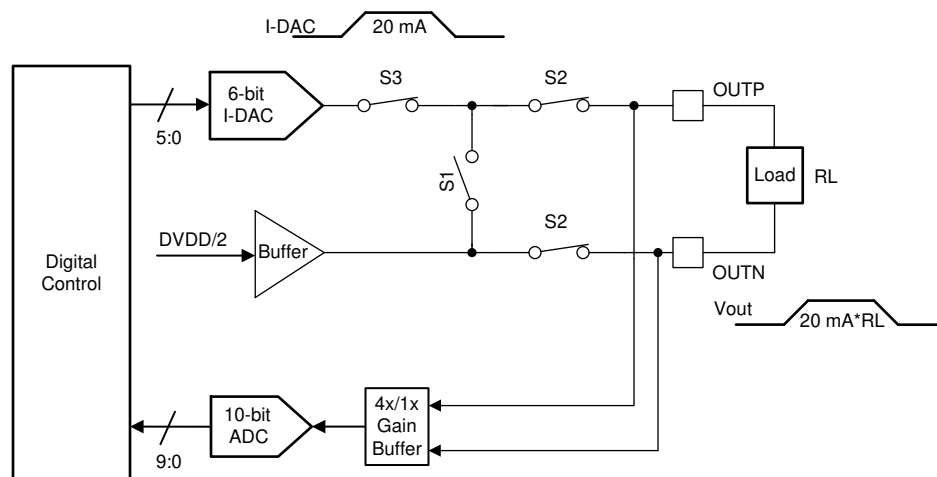


Figure 4. Simplified Block Diagram of SL and OL Diagnostics Circuitry

For the SL and OL diagnostics, S1 is opened, S2 and S3 are closed. OUTP pin is biased by the buffer to $\frac{1}{2}$ DVDD. A current DAC forces a 20-mA current flowing through the load. The internal 10-bit ADC measures the voltage and calculates the resistance across OUTP and OUTN. An OL fault will be identified if the following condition exists:

$$V_{OUTP/N} > 20 \text{ mA} \times \text{Open load threshold } (\Omega) \quad (1)$$

An SL fault is detected if the following is true:

$$V_{OUTP/N} < 20 \text{ mA} \times \text{Short load threshold } (\Omega) \quad (2)$$

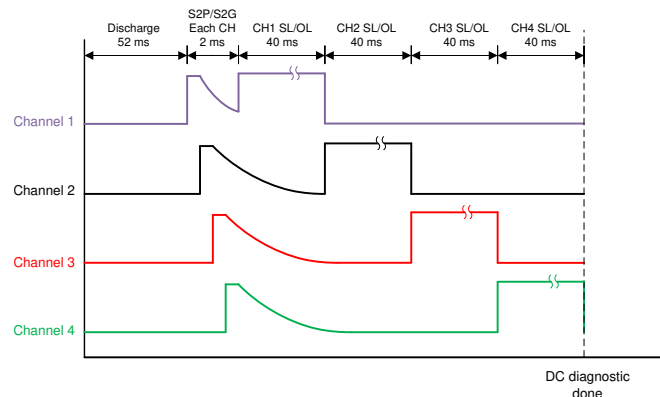
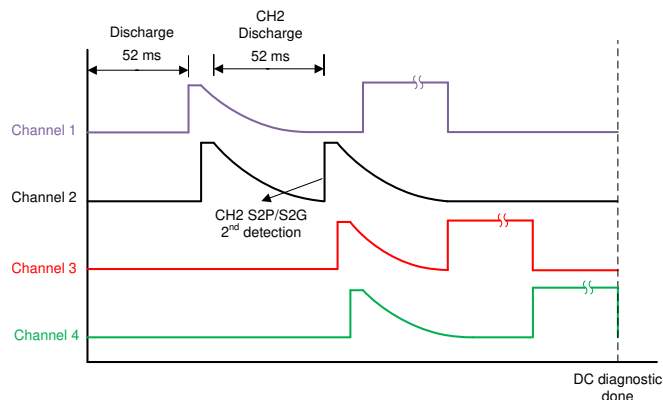
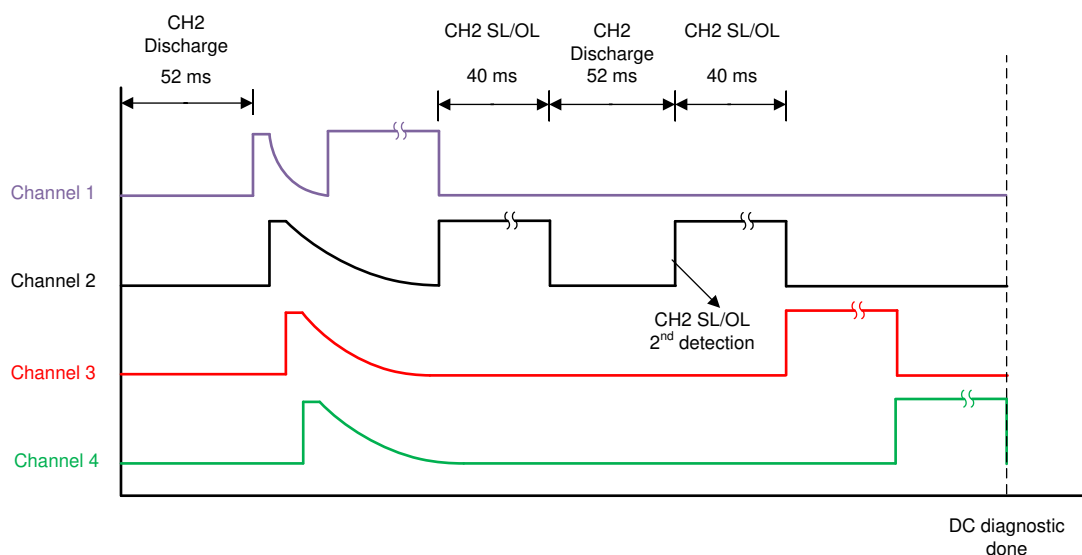
In *Line Out* mode, the OL threshold is adjusted to higher level. OL detection is not pop-free because there will be current flow through the load, which is the input of the external amplifier. In this case, the external audio amplifier should be muted to avoid any audible noise during the DC diagnostic.

2.2.3 DC Diagnostics Flow Chart and Timing

At the start of DC diagnostics, there is a 52-ms discharge time. This is for discharging the capacitors in output stage, avoiding incorrect diagnostic result caused by residual charge.

The DC diagnostics then tests for S2P and S2G detection. The detection is sequentially executed among the 4 channels, taking 2 ms for each channel. Once S2P or S2G fault on any channel is identified, the same detection will be repeated one more time after a 52-ms waiting time for discharge. If the fault is confirmed by the second detection, the device moves to next channel or diagnostic step.

SL and OL detection comes after S2P and S2G detection. It should be noted that if a specific channel failed in previous S2P and S2G detection, SL and OL detection on this channel will be skipped. SL and OL detection is also sequentially executed among the 4 channels, taking about 40 ms for each channel. Similarly with S2P and S2G, a second check will be executed a second time after a 52-ms waiting time for discharge. [Figure 5](#) shows a complete timing diagram for the case where no fault is detected. [Figure 6](#) shows the case where a S2P fault occurred on Channel 2. [Figure 7](#) shows the case where an SL fault occurred on Channel 2.


Figure 5. No Fault Case Timing Diagram

Figure 6. Channel 2 S2P Case Timing Diagram

Figure 7. Channel 2 SL Case Timing Diagram

3 AC Diagnostics

3.1 What is AC diagnostics

The AC diagnostics are used to identify if the AC coupled speaker is properly connected. It is done by measuring the impedance and phase shift across OUTP and OUTN pins. An external sine wave is required as providing stimulus to perform the AC measurement except on the TPA6404-Q1 and TPA6304-Q1 devices. The impedance and phase shift are reported in related registers. Users are responsible to determine if the measured values indicate a properly connected speaker.

3.2 Working Principle

Figure 8 shows the simplified block diagram of AC diagnostics circuitry.



To achieve high AC measurement accuracy, some calibration may be required based on the speaker characteristics. Contact TI if any support is needed on implementing the AC diagnostics on a specific platform. [Figure 9](#) shows an AC diagnostic example of two-way speaker load detection. The impedance of the woofer and AC coupled tweeter was measured by TAS6424 AC diagnostic and an audio analyzer, respectively. In this case, the TAS6424 AC diagnostic report showed good accuracy, and AC coupled tweeter disconnected condition was successfully identified.



4 Special Case Handling in DC Diagnostic

4.1 Back EMF

4.1.1 Application Scenario

As is well known, speakers are electroacoustic transducers that convert the electrical energy into acoustic energy - also known as sound. Speaker is also sensitive to vibrations and can generate a signal, like a microphone, and turn this in electrical energy. This energy is called an electromotive force and is generated by the voice coil vibrations. This electrical energy presented across the speaker terminals is called Back Electromotive Force (back EMF).

In an automotive audio system, back EMF mainly has two sources. One is transmitted through the air, such as the external noise that exists in the car assembly line environment or loud outside noises when driving on the road. The second major back EMF source is structure borne noise, which is caused by vibrations that are directly transmitted through the vehicle body structure. Examples are door slamming or the mechanical vibration during driving. Structure borne back EMF usually has a higher amplitude and a more significant impact, but also a shorter time duration. [Figure 10](#) illustrates the back EMF sources on vehicles.

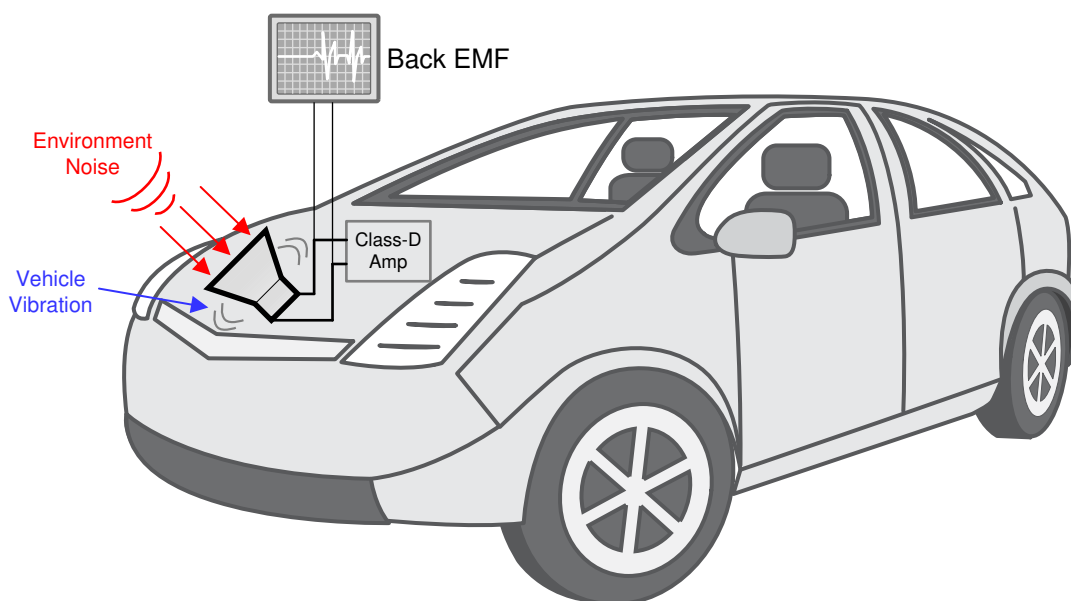
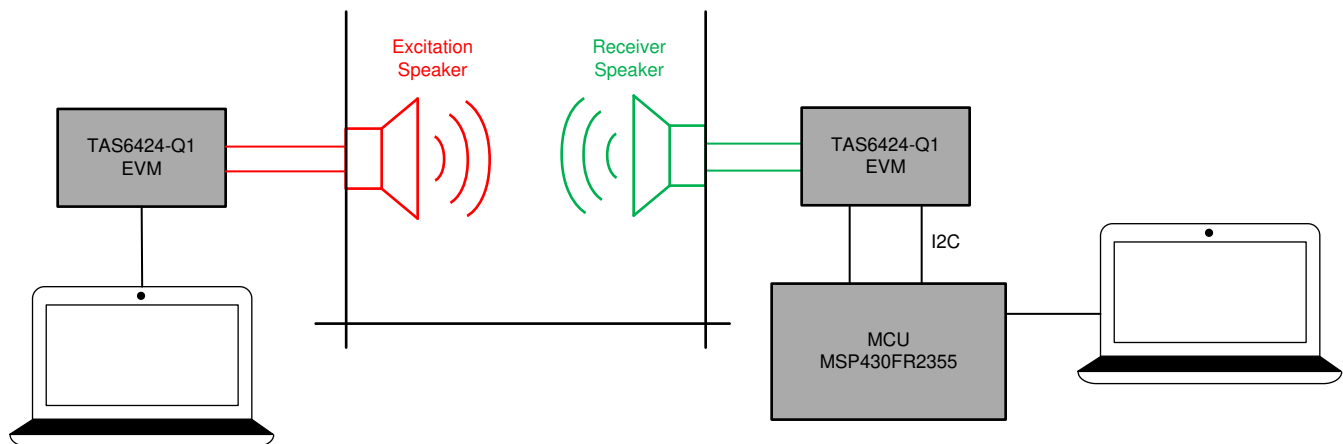


Figure 10. Back EMF on Vehicle Speaker

As discussed in [Section 2](#), the basic idea of DC diagnostics is to apply specific signals across the OUTP/N pins, detect the voltages on OUTP/N pins and determine the detected result. The back EMF can have an impact on the diagnostic procedure as it introduces electrical disturbances to the OUTP/N pins. This interference introduced by back EMF may lead to incorrect diagnostic results.

Tests are done to simulate the back EMF noise to evaluate its impact on the DC diagnostics procedure with the TAS6424-Q1 device. An excitation speaker plays the noise while a receiver speaker is placed nearby to pick up the noise and generate back EMF.

[Figure 11](#) shows the test setup.


Figure 11. Test Setup for Back EMF Impact on DC Diagnostics

On the excitation side, a 2-Ω speaker is driven by a TAS6424-Q1EVM, with 14-dB digital gain and 29-V analog gain setting. The volume on the laptop which operates as signal source is set to be max. The speaker plays a sound which is recorded during highway driving to simulate a noisy environment. On the receiver side, a 2-Ω speaker was closely placed as the receiver. The distance of the two speakers is adjusted to correlate the back EMF amplitude to real road conditions. The TAS6424-Q1 device on the receiver side is instructed to execute DC load diagnostics every 2 seconds. The reported diagnostic results are then compared with the real load condition. [Table 1](#) shows the test result.

Table 1. DC Diagnostic With Back EMF Test Result

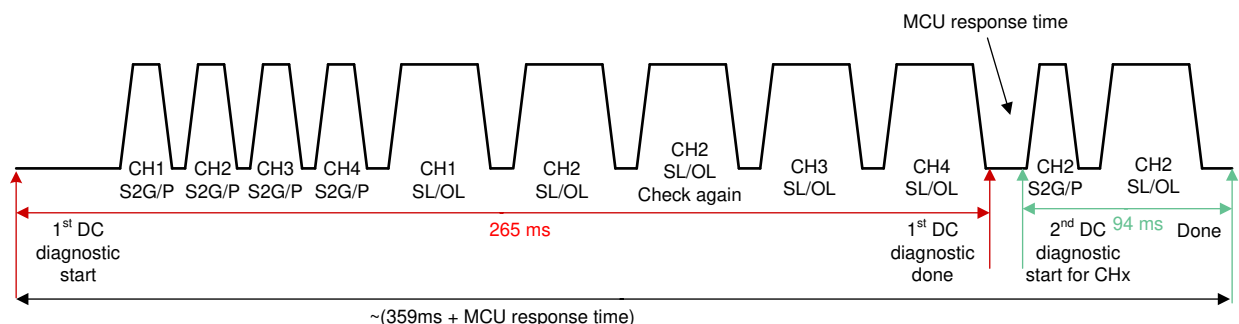
Load Condition	Incorrect Report Counts
Short Load	466 / 2.2%
Open Load	0
Short to GND	0
Short to Power	0
Total LD cycles	20871

In this case, the TAS6424-Q1 device on the receiver side is expected to report no fault on its load. However, the test results indicate that the shorted load is incorrectly reported during 2.2% of the tests.

4.1.2 Back EMF Handling – Best Practice

To improve the DC diagnostics reporting accuracy under back EMF, two practices are proposed.

The first is to repeat DC diagnostics on the specific channel which has reported a fault condition. This method can effectively avoid the impact of transient back EMF caused by vehicle body vibration due to their short duration. The timing diagram of this approach is shown in [Figure 12](#).


Figure 12. Timing Diagram of Repeated DC Diagnostics

The diagram shows a case in which the transient back EMF happens on Channel 2 during DC diagnostics. After reading the result, the MCU or processor sends a repeat command to execute the DC diagnostics only on Channel 2 and reads the result again.

Figure 13 shows the flow chart of this approach.

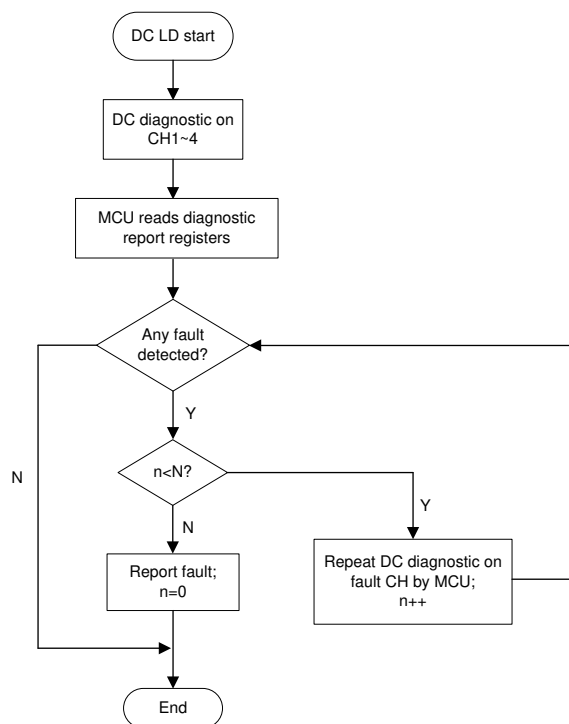


Figure 13. Flow Chart of Repeated DC Diagnostics

A third or even fourth run can also be made if the fault is still present. The re-run command needs to be sent by the MCU or processor via I2C bus if the diagnostic procedure is manually triggered. If the DC diagnostics are triggered automatically before entering MUTE or PLAY mode, the device will keep re-trying without a control command being needed if any fault is detected. It is easy to implement and suitable for handling the strong transient back EMF caused by vehicle body vibration.

Table 2 shows the results of the same experiment used to validate this approach.

Table 2. Test Result of Repeat DC Diagnostic

Load Condition	Incorrect Report Counts	Incorrect Report Counts (After 2nd Run)
Short Load	466 / 2.2%	530 / 1.7%
Open Load	0	0
Short to GND	0	0
Short to Power	0	0
Total LD cycles	20871	30642

After the practice is applied, where a second DC diagnostic is added, the incorrect diagnostic result percentage decreased to 1.7%. With an increased number of DC diagnostic re-runs, it is expected that the possibility of an incorrect report result decreases further, at the cost of an increased diagnostic time.

Another approach, also a more reliable one, is to implement AC diagnostics to double check the channel which has reported a fault condition after DC diagnostics. AC diagnostics results deliver impedance and phase shift measurements across OUTP/N pins, both of which can be used to identify faulty load conditions. According to FFT analysis, major energy of noise introduced by back EMF distributed below 100 Hz. The recommended stimulus frequency range is 10 kHz to approximately 20 kHz for AC diagnostics and is well above the noise distribution in the frequency domain. The basic idea is that the detection circuitry in AC diagnostics only responds to high-frequency signals. It can be recognized as a “high-pass filter” to keep the detection free from the influence of the low frequency back EMF signal.

Figure 14 shows the timing diagram of the DC + AC diagnostics.

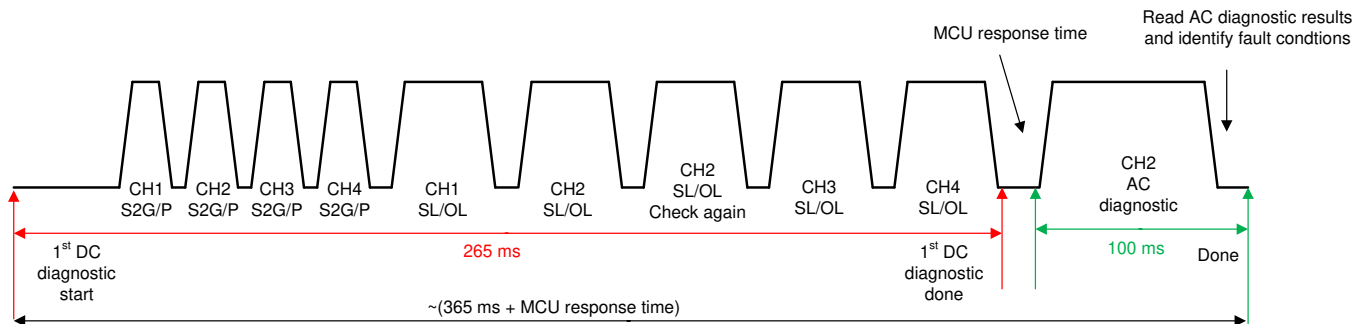


Figure 14. Timing Diagram of DC + AC Diagnostics

Figure 15 shows the flow chart of the DC + AC diagnostics.

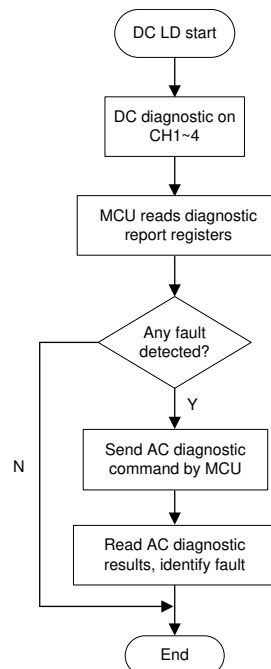


Figure 15. Flow Chart of DC + AC Diagnostics

Once a fault condition is detected in DC diagnostics, the MCU reads the report registers and sends a command to run AC diagnostics on channels which reported a fault. Afterwards, the MCU reads the AC diagnostics result and identifies if it is a real fault. On the TAS6424-Q1 device the stimulus signal used during AC diagnostic needs to be provided by the audio interface.

The same experiment from [Section 2](#) was done. Two different AC diagnostic stimulus frequencies were used. [Table 3](#) shows the test results. It indicates that the DC + AC workaround always reports the correct diagnostic results with a success rate of 100%.

Table 3. DC + AC Diagnostics Test Results

Load Condition	Incorrect Report Counts (Test Frequency = 10 kHz)	Incorrect Report Counts (Test Frequency = 19 kHz)
Short Load	0	0
Open Load	0	0
Short to GND	0	0
Short to Power	0	0
Total LD cycles	20871	30642

To further validate the robustness of the proposed method, the experiment was done in reverse. The receiver speaker was placed in different fault conditions and the results showed that the DC + AC workaround reported the diagnostic results correctly with a success rate of 100%, as shown in [Table 4](#).

Table 4. DC + AC Diagnostics in Real Fault Condition Test Results

Load Condition	Stimulus Frequency in AC LD	Correct Percentage
Shorted Load	10 kHz	817/817 = 100%
	19 kHz	770/770 = 100%
Open Load	10 kHz	720/720 = 100%
	19 kHz	724/724 = 100%

4.2 Running DC Diagnostics on AC Coupled Speakers

4.2.1 Application Scenario

In some automotive audio applications, the tweeter is AC coupled by a large series capacitance to build a high-pass filter. For the AC coupled speakers, the best practice is to use AC diagnostic to identify the loading condition. However, due to some limitations in specific scenarios, it is still needed to run DC diagnostics on AC coupled speakers.

As introduced in [Section 2.2](#), the device applies a specific signal pattern in the DC diagnostic procedure. In SL, OL detection, the large series capacitance is charged by the detecting current, and then discharged once an available loop shows up in the following device actions. This behavior could result in pop noise and incorrect DC diagnostic results.

Tests are set up to evaluate the AC coupling capacitor impact with the TPA6404-Q1 device. An ITU-R filter box is used for the pop noise level measurement. Test conditions are listed in [Table 5](#). [Figure 16](#) shows the AC coupled speaker setup, and also the internal diagnostic circuitry for proper understanding.

Table 5. Test Condition for Running DC Diagnostic on AC Coupled Speaker

Test Condition	Values
PVDD, VBAT	14.4 V
Output filter	3.3 μ H + 1 μ F
Speaker resistance	4 Ω
AC coupling capacitor	100 μ F

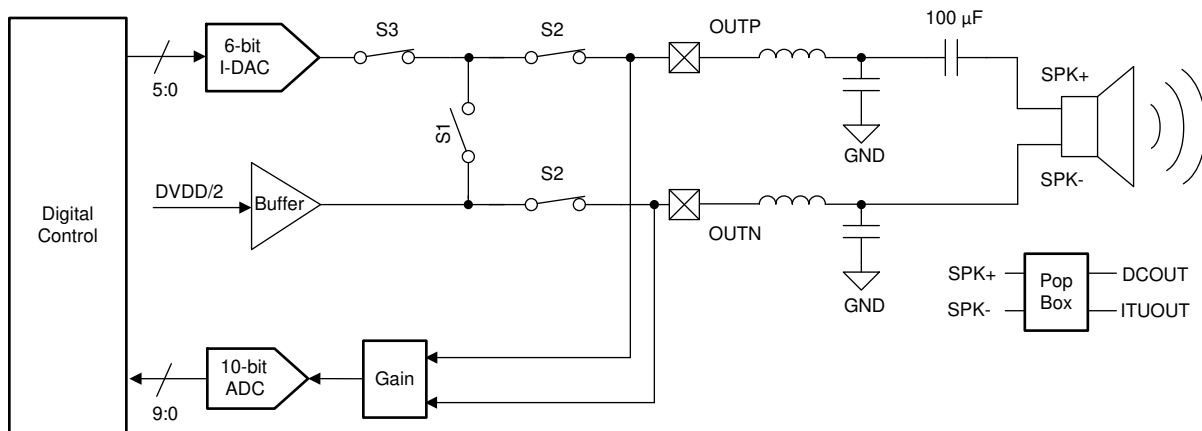


Figure 16. Test Setup for Running DC Diagnostic on AC Coupled Speaker

Figure 17 shows the test results.

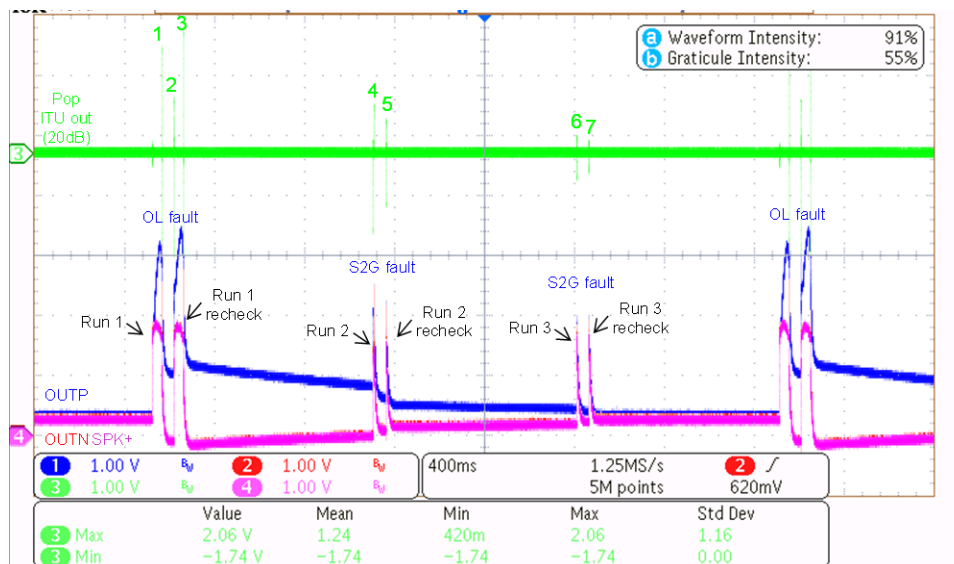


Figure 17. Test Result for Running DC Diagnostic on AC Coupled Speaker

A few pop noises and incorrect DC diagnostic report can be identified in the waveform. For ease of describing, the runs were marked with a number. Pop noises and the fault diagnostic reports were also labeled.

Figure 18 shows the time scale zoomed-in waveforms of Run 1.

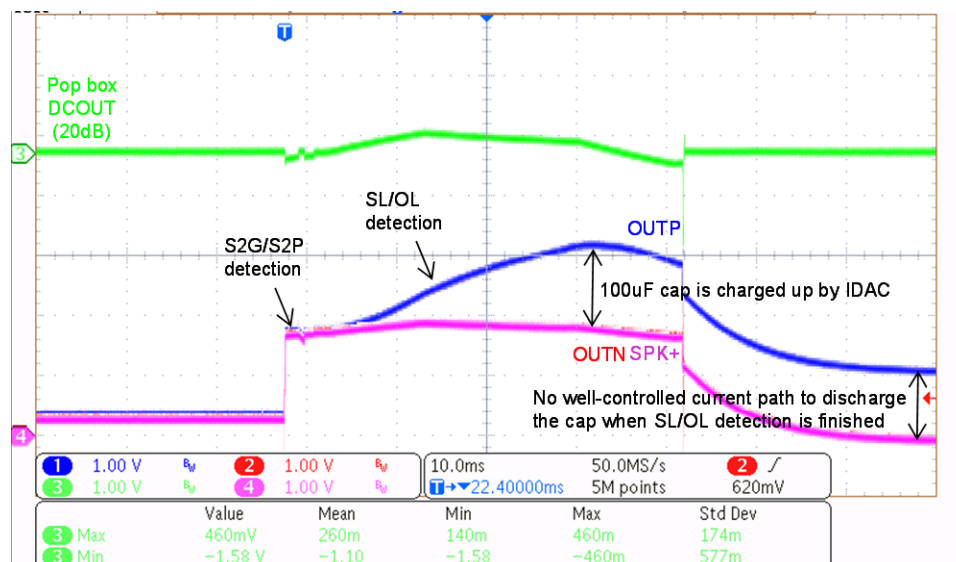


Figure 18. Time Scale Zoomed-in Waveform of Run 1, First Check

At the beginning of the DC diagnostic, S2P, S2G detection was executed and passed. In the following SL, OL detection, an OL fault was detected as expected. A recheck was then executed, reporting the same OL result. One thing to be noted, during the SL, OL detection, the detection current flowed from OUTP to OUTN and charged the AC coupling capacitor up, as shown in Figure 19.

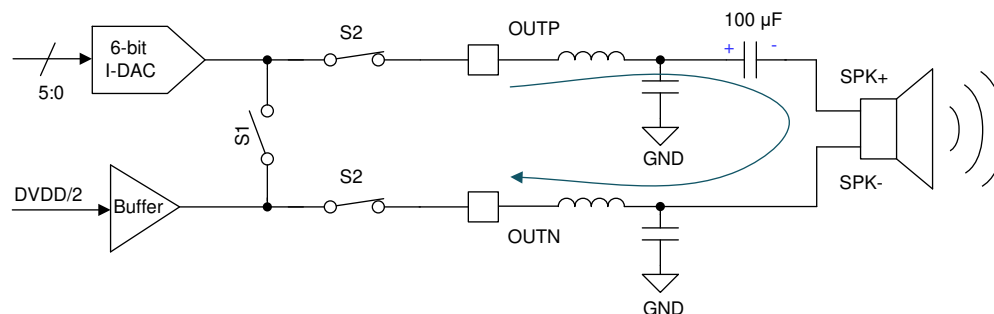


Figure 19. Simplified Block Diagram for SL, OL Detection

Once the detection was finished, S2 was opened. There was no well-controlled path for the large AC coupling capacitor to discharge. The charge was sustained until next diagnostic action. The voltage kept on the AC coupling capacitor was measured as about 1.5 V.

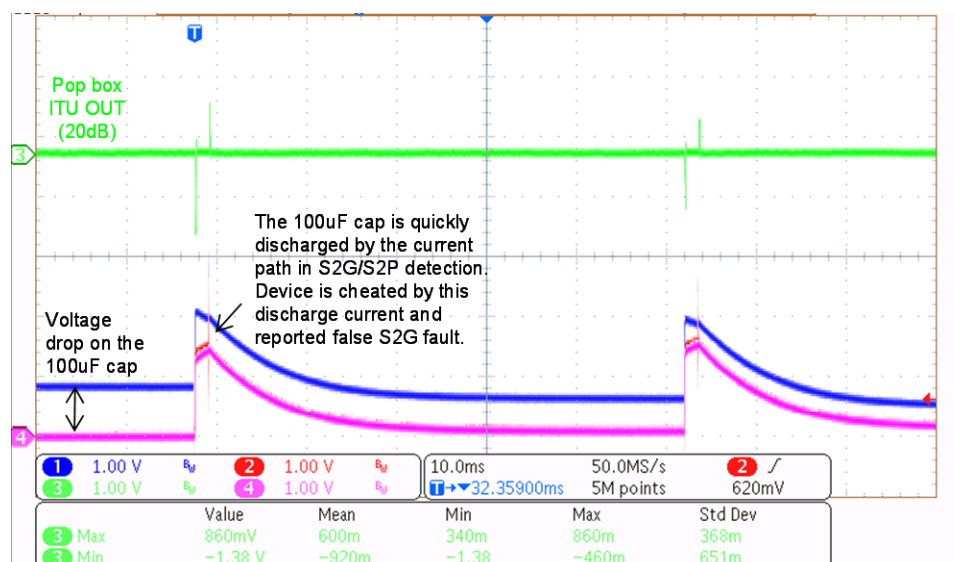


Figure 20. Zoom-in Waveform of Run 2 and Run 3

As a fault condition is identified, Run 2 and Run 3 were executed automatically. Figure 20 shows the zoom-in waveform. After about one second, Run 2 began by closing the S1 and S2. This developed a discharging path as shown in Figure 21. As the result, a voltage was developed across the S2 (on OUTN leg), making the voltage on OUTN lower than S2G threshold, thus a S2G fault was reported. On the other hand, after discharging during S2G, S2P detection in Run 2, the AC coupling capacitor still maintained some charge, which caused the following Run 3 to report S2G for the same reason.

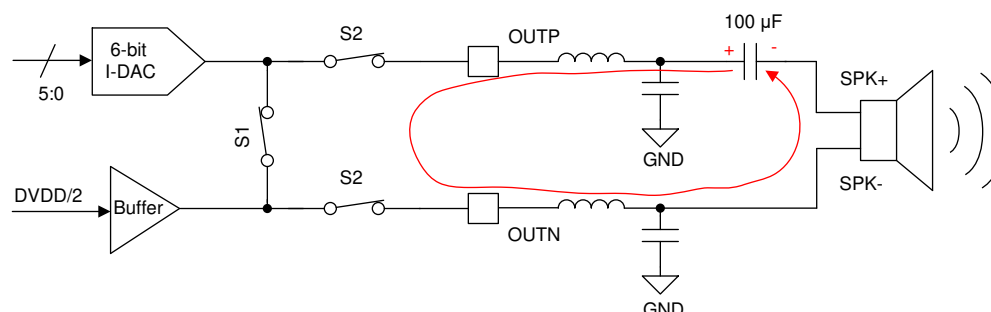


Figure 21. AC Coupling Capacitor Discharging Path at the Beginning of Run 2

Pop noises occur due to the current flowing through the speaker. This is the mechanism that created Pop 2, 4, 5, 6, and 7. Figure 22 shows the zoomed-in waveform to observe pop noise details in Run 2.

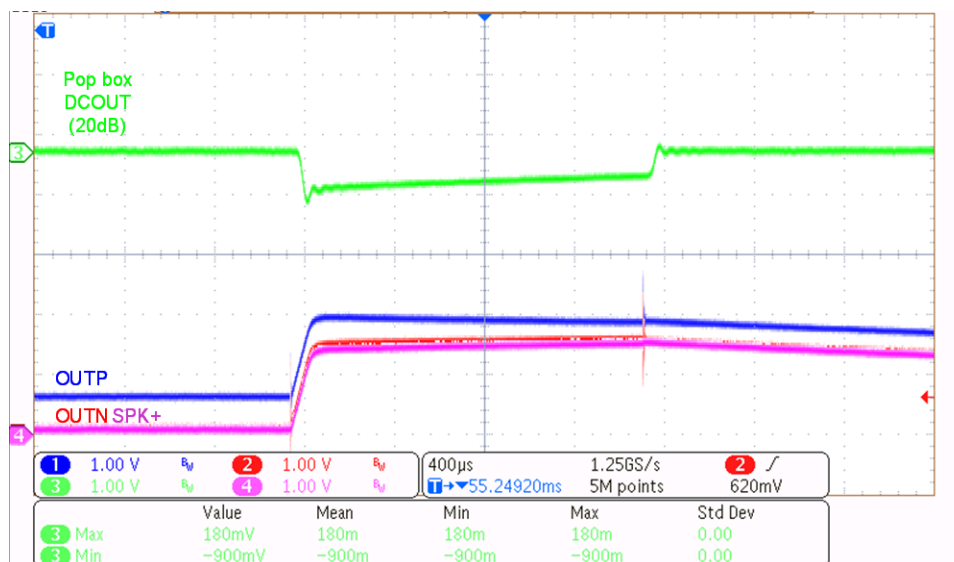


Figure 22. Zoomed-in Waveform of Pop 2, 4, 5, 6, and 7

The amplitude of Pop 2, 4, 5, 6, and 7 were in the range of 60 to approximately 160 mV. As the AC coupling capacitors discharged in Run 2 and 3, pop noise level was decreasing from Pop 4 to 7.

Run 1 is zoomed-in to observe the Pop 1 and Pop 3, as shown in Figure 23. It can be identified that these pop noises happened right after the SL, OL detection was finished.

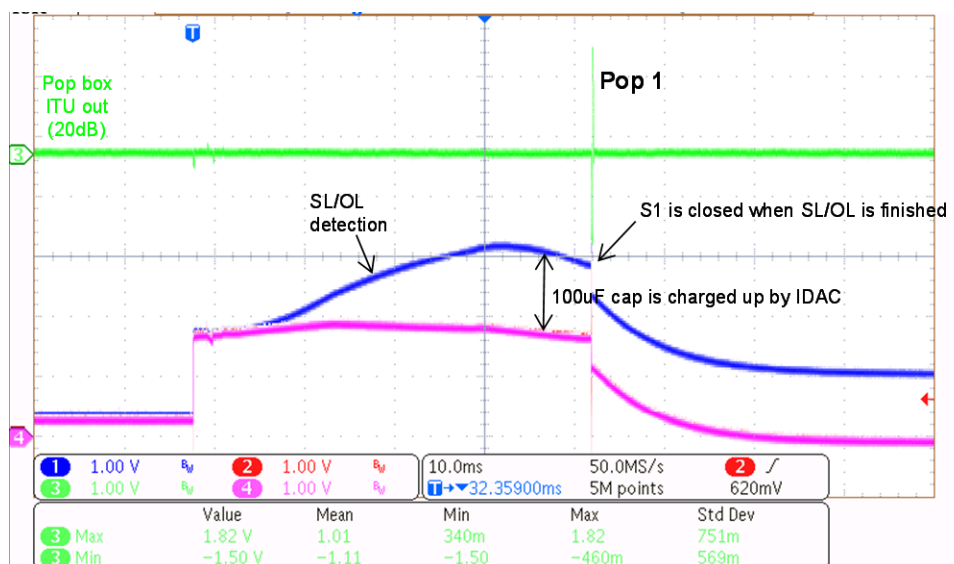


Figure 23. Zoomed-in Waveform of Run 1

To reveal more detail, Pop 1 is further zoomed in as shown in Figure 24.

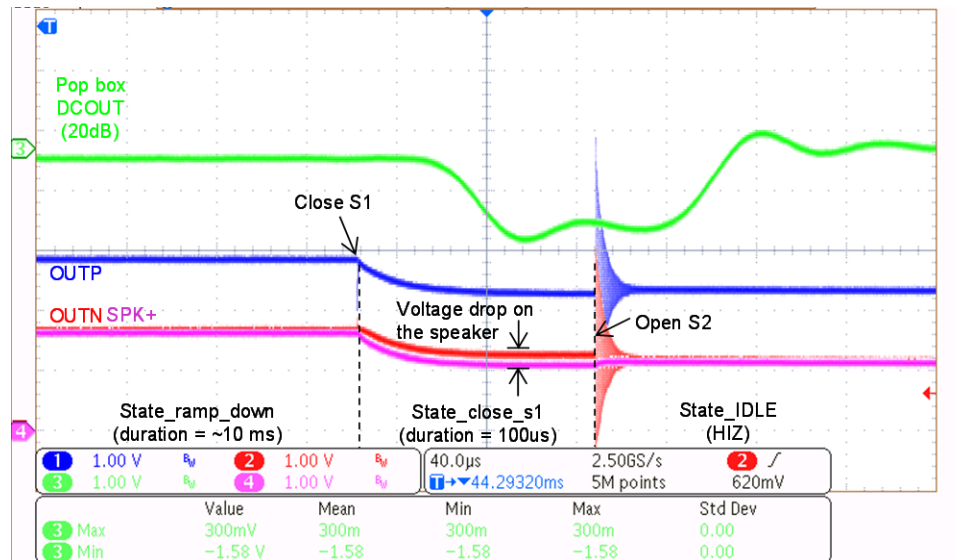


Figure 24. Further Zoomed-in Waveform of Pop 1

During the SL, OL detection, S1 is open and S2 is closed. After the detection, the device returned to idle status with S1 closed and S2 opened. However, at the moment the detection finished, closing of S1 and opening of S2 were not done simultaneously. There was an approximate 100- μ s time overlap between when S1 was closed first and S2 was then opened. This behavior developed the same AC coupling capacitor discharging path, as shown in Figure 21. Also, at this time, the AC coupling capacitor was just charged during the SL, OL detection and holding a relatively high voltage, so the Pop 1 and Pop 3 had a higher level than others. The amplitude was about 200 mV with approximately 100- μ s duration.

4.2.2 Running DC Diagnostic on AC Coupled Speaker – Best Practice

Based on the analysis in Section 4.2.1, providing a discharge path for the AC coupling capacitor is the essential way to handle this special case. One implementation is to add a resistor in series with an inductor across the OUTP and OUTN, as shown in Figure 25.

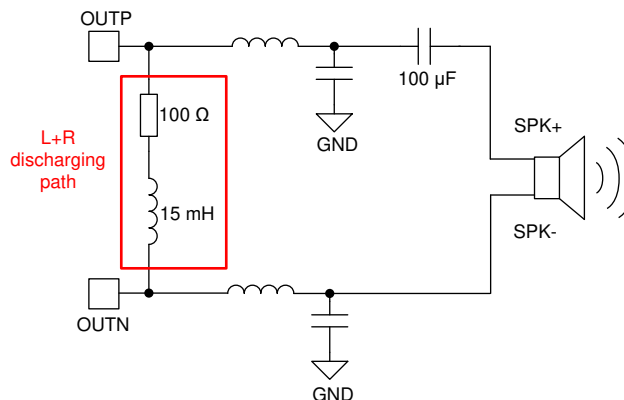


Figure 25. Adding a Series L and R Branch

This provides a discharging path for the AC coupling capacitor which is always available, regardless of the diagnostic switches status inside the IC. A low impedance of the series L and R branch helps quickly discharge the large AC coupling capacitor. However, it also increases the power loss on it during normal audio playback.

In AC coupling speaker applications, the SL, OL detection result should be ignored and then use the AC diagnostic to check the speaker connection. However, if an OL fault report is indeed required, the lower limit of the R has to be determined by the OL detection threshold (70 Ω according to data sheet). Another design balance is about the inductor. Higher inductance is better to block the current through the L + R branch, but this also means a larger inductor size.

TI recommends using 15 mH + 100 Ω as a start for the L + R branch. Figure 26 shows the test result after the L + R branch applied across OUTP and OUTN. It indicates that the fault S2G reports are eliminated, and the pop noise level decreased to approximately 60 mV according to the measurement.

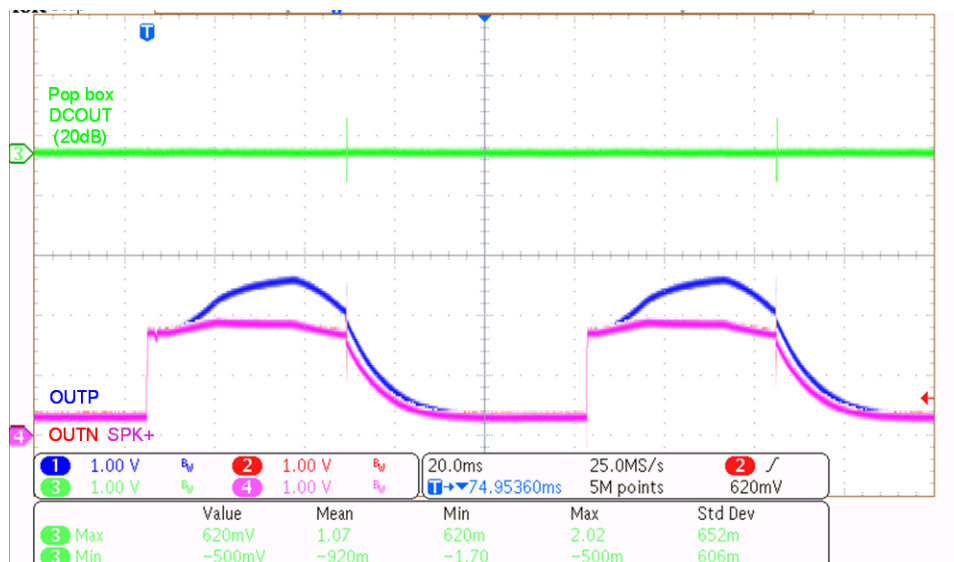


Figure 26. Test Result After Applying an L + R Branch Across the OUTP/N

A lower pop noise level could be achieved by decreasing the resistance value, at the expense of more power loss on the L + R branch. System designers can make further adjustment on the values to balance the pop suppression and extra power dissipation in their applications.

5 Summary

This application note introduced the concept and the basic working principle of load diagnostics on TI automotive class-D audio amplifiers. Back EMF handling and running DC diagnostics on AC coupled speakers are also discussed as special cases, with TI recommendations to solve these cases.

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