# TITLE: Correct implementation of the USB Input Circuit



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## *Contents*

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# *1-Introduction:*

Following the Design Review meeting held at ITCL on April 17th a team was set up to investigate the problems related to the USB-DAC input circuit used in certain USB applications. The USB speaker DSS350 was the application used to carry out this investigation and the results obtained are to be verified for the other USB applications. The first task of the team was to investigate the function of the 4-coil common mode choke (component number 5625) and to investigate why the circuit works with 4-coil common mode choke but it is said not to work when no coils are used since both configurations are correct in theory and they should both work. The 2-coil common mode choke configuration, used in the DS350, was found to be theoretically wrong and it should give rise to errors due to the type of signalling used in USB (Single Ended Zero), this is also to be demonstrated experimentally. Firstly, the all coil configurations were tested by connecting the DSS350 to the PC host via the Universal Host Control Interface (UHCI). The successful configurations obtained in the previous set up were then tested using various USB applications more prone to errors such as connecting the DSS350 via a hub monitor and via Open Host Control Interface (OHCI). Finally, the application input circuit configurations that yielded correct performance are presented in the last section of this report as the recommended implementation of the USB input circuit.

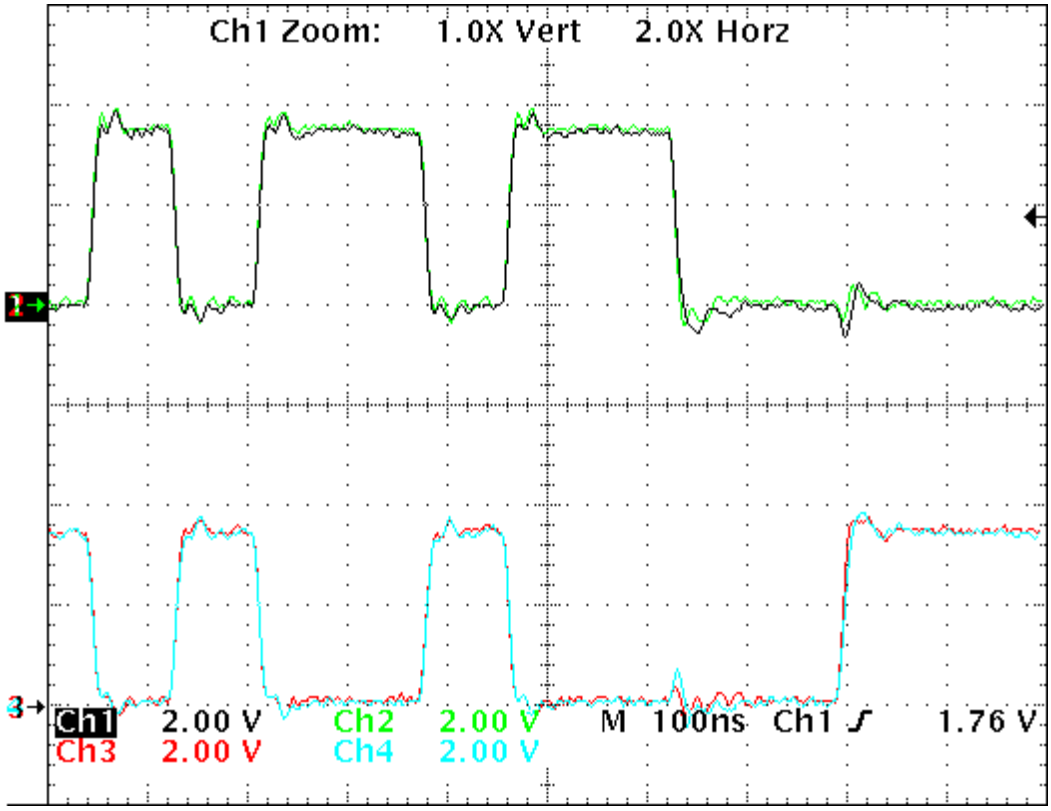
# *2- DSS350 connected via UHCI:*

The DSS350 was first connected to the host computer using all coil configurations and the End of Packet (EOP) USB waveforms were observed using in order to investigate what happens when the differential lines go into the single Ended Zero State which was thought to be the main source of problem in USB signalling. The USB port for the host PC was implemented by means of a motherboard built-in UHCI.

## *2.1- Input circuit using 4-coil common mode choke*

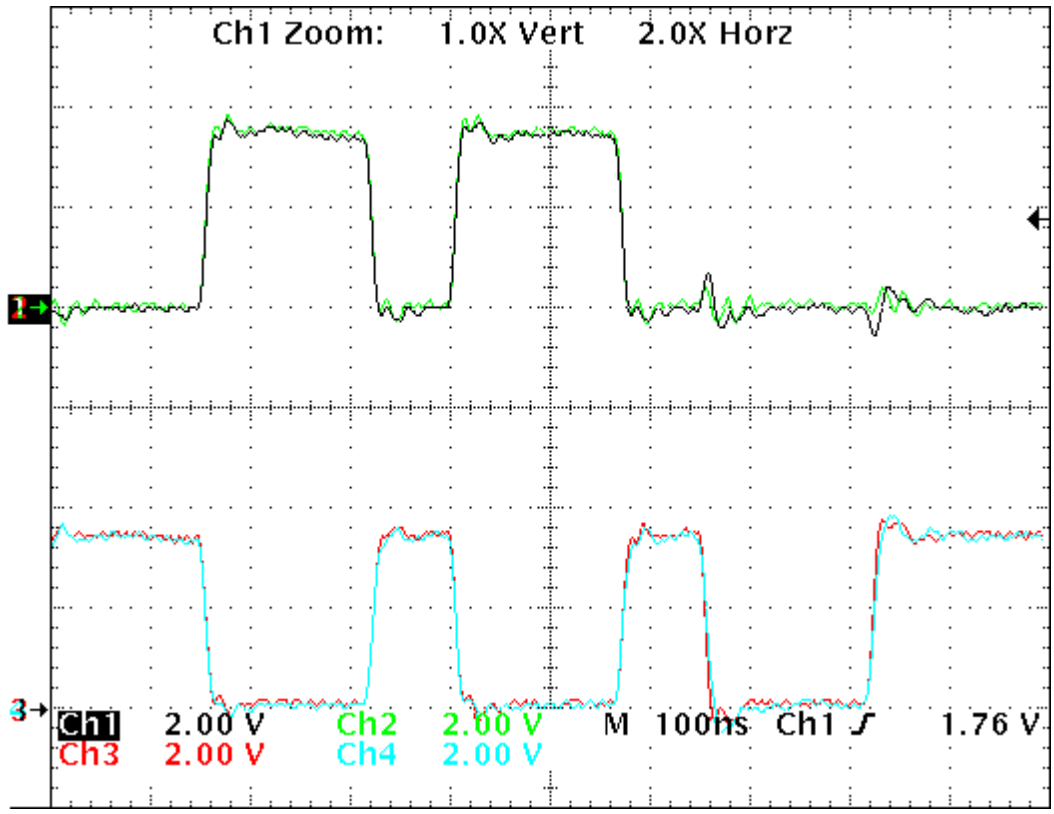
The USB waveforms were observed when the TDK ZJY-M4A 4-common mode choke is used in the USB DAC input circuit, as shown in the Application Diagram (Fig.9) of the UDA 1331H. The waveforms obtained for last bit being a 1 or a 0 are depicted below in Figure 1 and Figure 2. Note that the USB speaker using this configuration was found to work correctly and neither sound cracks nor malfunctioning of the volume control occurred. Therefore, these waveforms can be taken as the normal waveforms for a working device. From both figure 1 and 2 it can be observed that little spikes occurred when the differential lines D+ and D- are forced into the Single Ended Zero state (i.e. both lines are pulled down to ground simultaneously).

By: Javier Lopez and Bruno Putzeys version 1.0 98-04-30




Ch1: Coil Output D- Ch2: Coil Input D- Ch3: Coil Input D+ Ch4: Coil Output D+

**Fig. 1:** USB Data lines using 4-coils with last bit being "0".

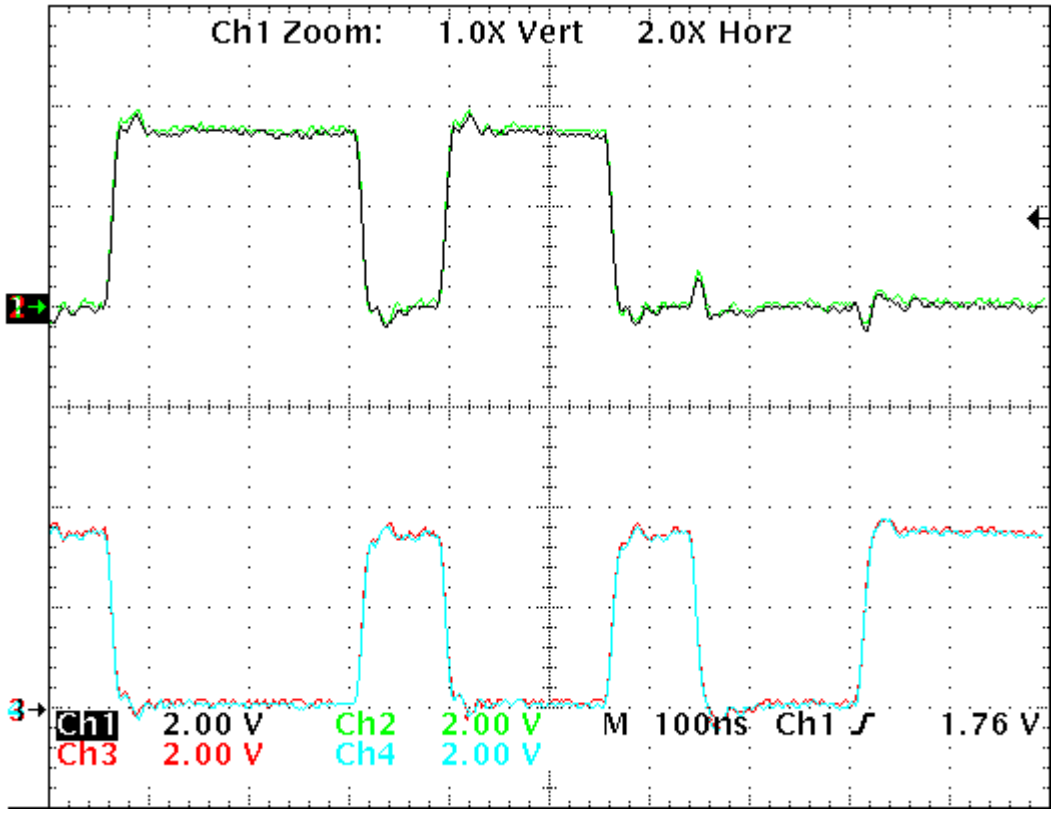



Ch1: Coil Output D- Ch2: Coil Input D- Ch3: Coil Input D+ Ch4: Coil Output D+

**Fig. 2:** USB Data lines using 4-coils with last bit being "1".

### *2.2- Input circuit using no coil common mode choke*

The TDK ZJY-M4A 4-common mode choke was short-circuited, so it was effectively removed from the USB DAC input circuit, and the rest of the input circuit was left unchanged. This configuration work perfectly, in spite of some of the claims made during the design review meeting, and this confirmed the theory stating that a circuit without coils was also correct. This result indicates that the coils do not seem to be doing anything in the circuit, and there is no need for them to be present unless EMC problems are reported. The Data lines of the USB Audio Packet were also observed and they were found to be almost identical to those observed when using a 4-coil common mode choke. These waveforms are shown below in Figure 3.

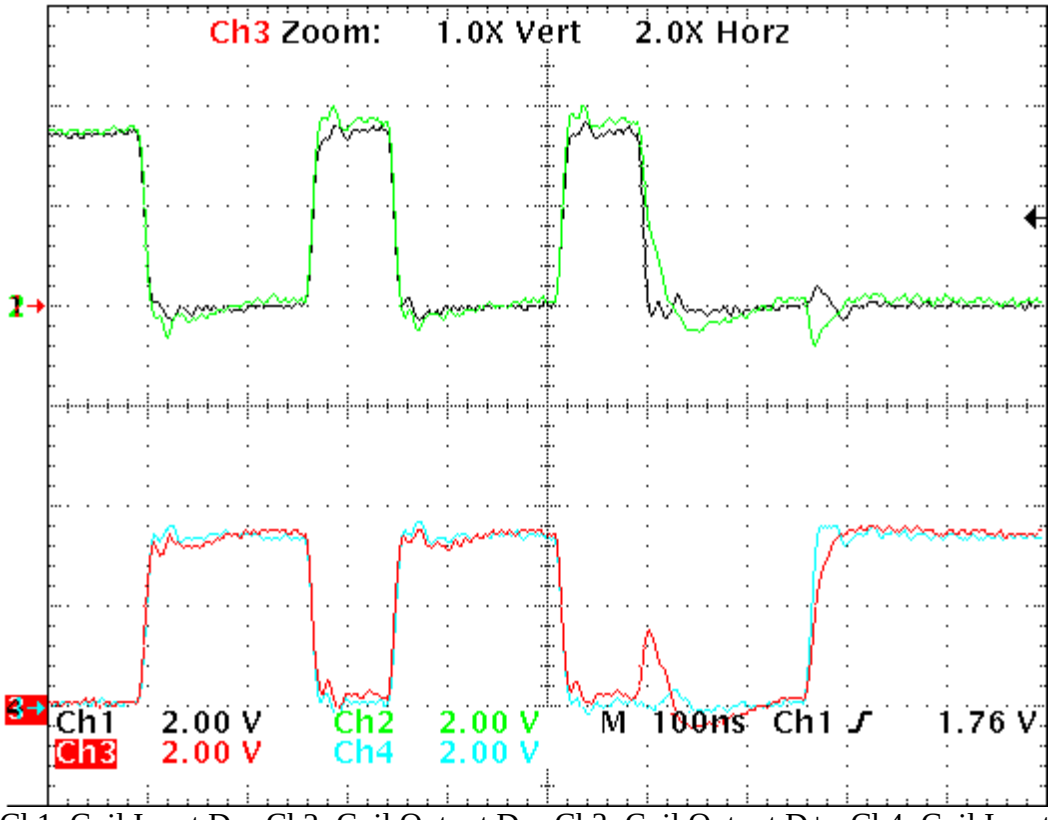



Ch1: Coil Output D- Ch2: Coil Input D- Ch3: Coil Input D+ Ch4: Coil Output D+

**Fig. 3:** USB Data lines using no coils with last bit being "1".

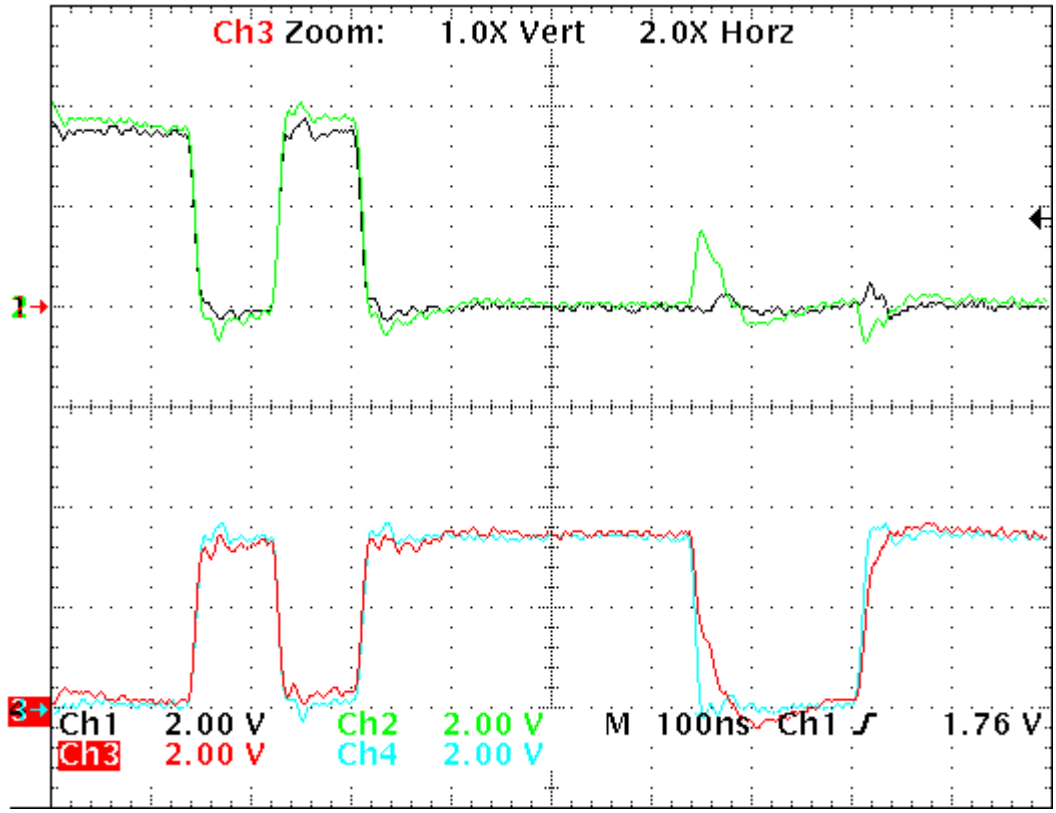
### *2.3- Input circuit using 2-coil common mode choke in data lines*

Finally, the DSS350 was tested when the USB input circuit was implemented using a 2-common mode choke in the differential data lines, and 2 ferrite beads for the supply and the ground lines. With this configuration the speakers generated sound cracks every few seconds and the volume keypad did not respond when pressed. This observation agrees with the statement made during the meeting about this configuration saying that it will cause problems when the differential lines are forced to ground (i.e. operate as a single line) simultaneously. The waveforms obtained for last bit being a 1 or a 0 are depicted in Figures 4 and 5. From these waveforms it can be seen that when the lines go into single ended zero state at EOP the common mode coil tries to keep the Data Lines differential and this results in voltage spikes line which in some cases will be large enough to cause false transitions at the USB input. If a false transition occurs, the USB-DAC is not able to detect the EOP and therefore the Audio Data Packet is lost and this results eventually in an audible crack in the Speaker sound. The waveforms illustrate quite clearly these observations.




Ch1: Coil Input D- Ch2: Coil Output D- Ch3: Coil Output D+ Ch4: Coil Input D+

**Fig. 4:** USD Data lines using 2-coils with last bit being "0".




Ch1: Coil Input D- Ch2: Coil Output D- Ch3: Coil Output D+ Ch4: Coil Input D+

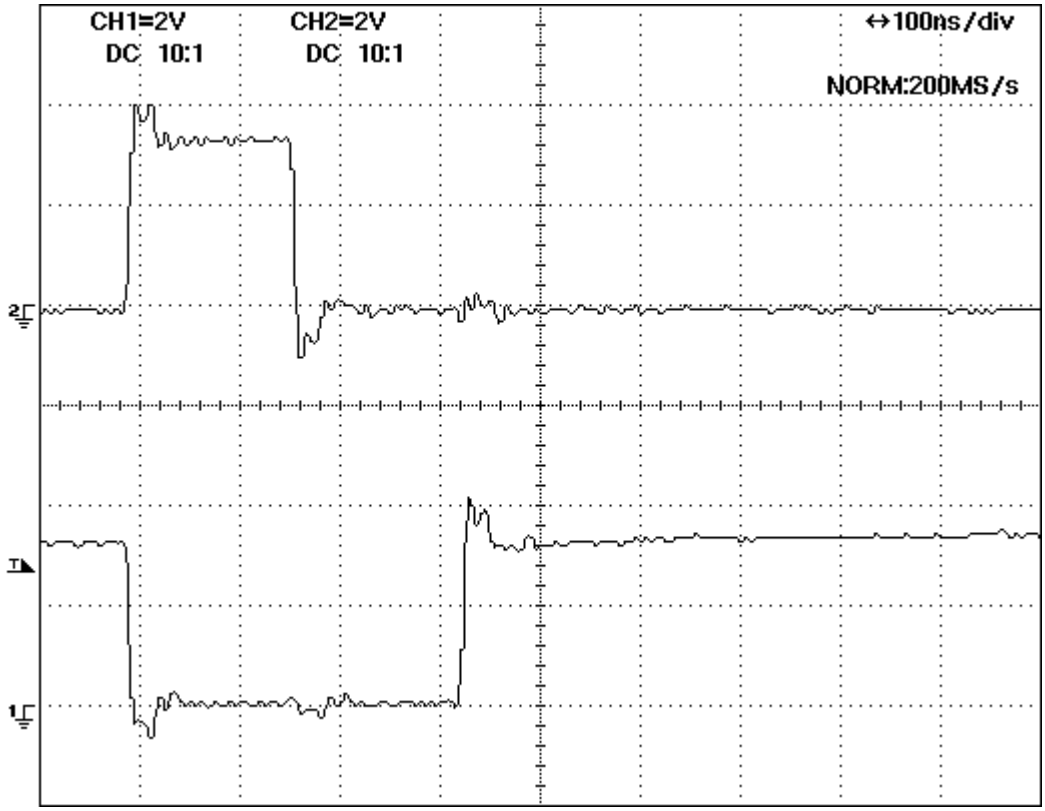
**Fig. 5:** USB Data lines using 2-coils with last bit being "1".

## *3- DSS350 connected via Philips Monitor Hub:*

Once the measurements connecting DSS350 via Universal HCI were completed, the USB UHCI port of the host PC was then connected to a Monitor which has 4 USB ports and acts as a USB Hub. The DSS350 was then connected via one of USB ports of the Monitor Hub. For this arrangement only the 4-coil and no-coil configurations were tested since the 2-coil configuration proved to be inadequate both in theory and in practice.

### *3.1- Input circuit using 4-coil common mode choke*

The USB waveforms were observed when the TDK ZJY-M4A 4-common mode choke is used in the USB DAC input circuit. These waveforms are shown below in Figure 6. The speakers were found to work correctly producing an audio output free of cracks and with the volume keypad responding when pressed. From the waveforms in Figure 6 it can be seen that the USB no voltage spikes are induced in the Single Ended Zero State. Note also that the USB waveforms generated by the Monitor Hub have significant ringing, although this did not affect the performance of this particular application, it may worsen the performance of more sensitive USB applications and therefore an improvement in the USB driver circuit of the Philips Monitor Hub would be highly desirable to obtain a more reliable product.

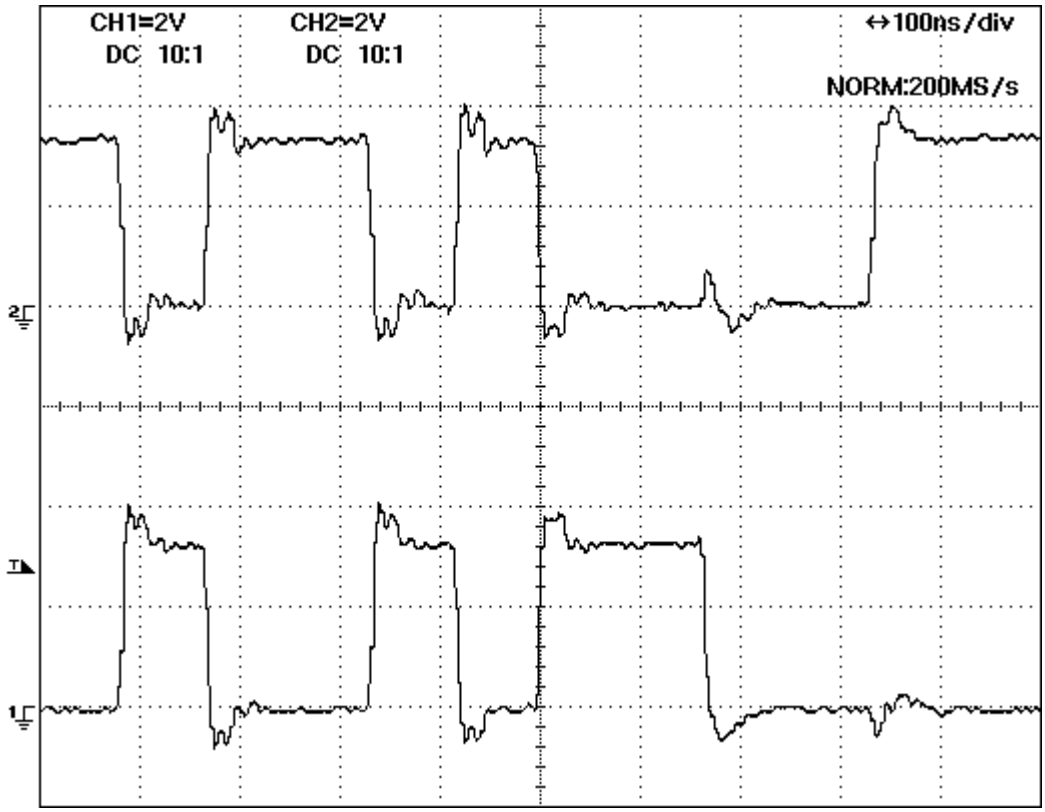



Ch1: Coil Output D+ Ch2: Coil Output D-

**Fig. 6:** USB Data lines when connected via Hub Monitor using 4-coils.

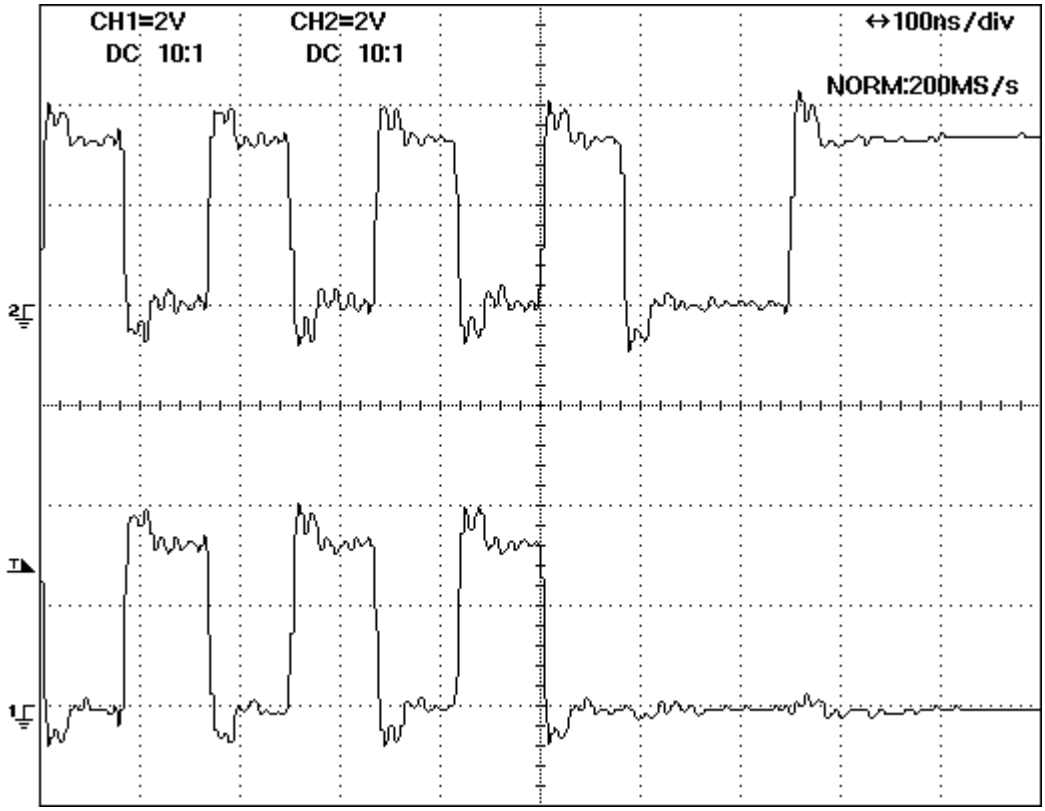
### *3.2- Influence of the ferrite beads in the input circuit*

The DSS350 was then tested with the 2-coil common mode choke removed but keeping the 2 ferrite beads in the supply and ground line. The presence of the 2 ferrite beads gives rise to a voltage spike for the Single Ended Zero, as can be observed below in Figure 7. In addition, the volume control circuit also failed to respond on certain occasions. The 2 ferrite beads were removed from the circuit to verify that the voltage spikes and the occasional keypad volume failures occurred due to their presence in the circuit and as expected their removal from the circuit resulted in the spikes also being removed as can be observed from Figure 8.




Ch1: Coil Output D- Ch2: Coil Output D+

**Fig. 7:** USB Data lines when connected via Hub Monitor using no common mode coils and 2 ferrite beads.




Ch1: Coil Output D- Ch2: Coil Output D+

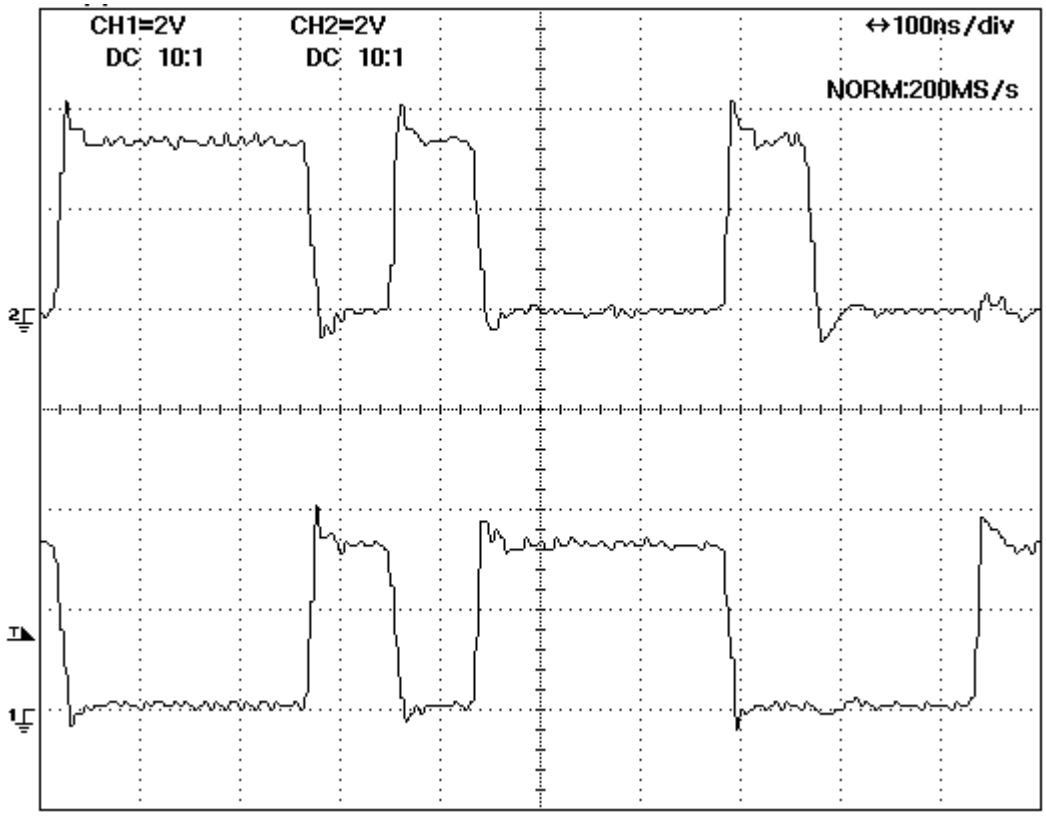
**Fig. 8:** USB Data lines when connected via Hub Monitor using no-common mode coils and no ferrite beads.

## *4- DSS350 connected via OHCI:*

Finally, the DSS350 was connected to the host computer via Open HCI cards from different manufacturers. The 4-coil and no-coil/no-bead configurations were tested for each card from a different manufacturer.

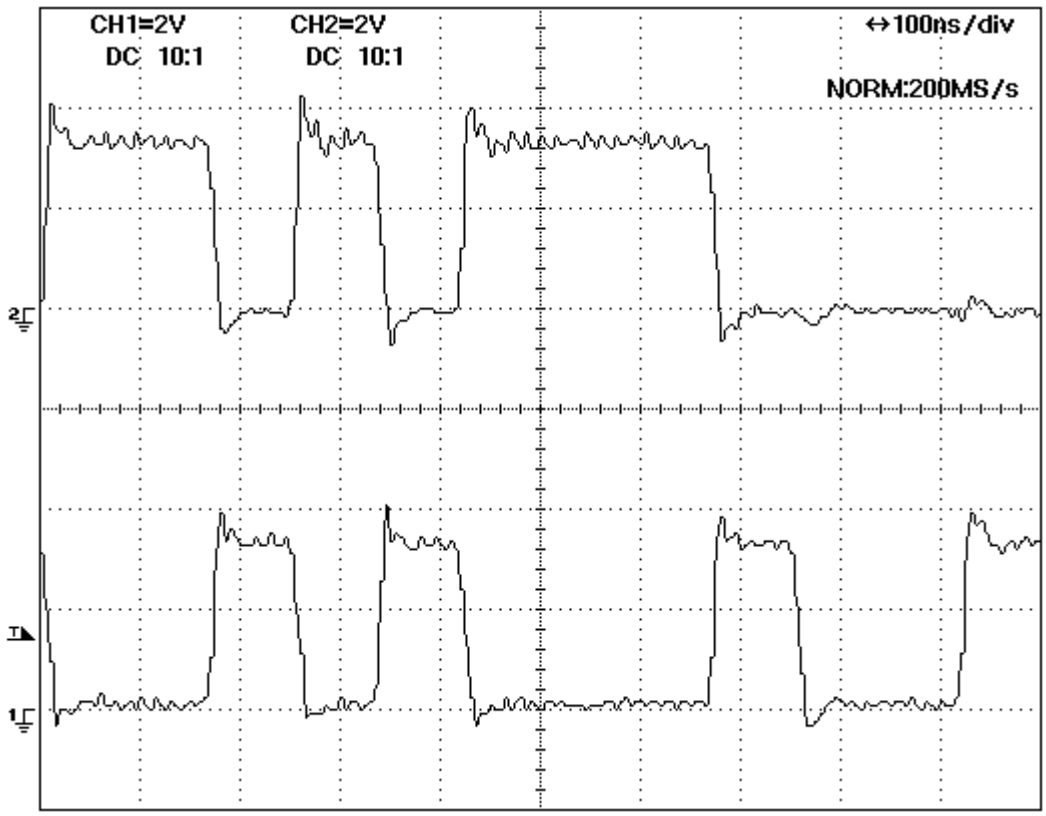
### *4.1- OHCI from Compaq*

The Compaq OHCI was the first one to be tested and it was found to work correctly for both no-coil and 4-coil configurations. The resulting USB data waveforms for each configuration are shown in Figures 9 and 10. As expected, the waveforms for both configurations were found to be almost identical.




Ch1: Coil Output D+ Ch2: Coil Output D-

**Fig. 9:** USB Data lines when connected via Compaq OHCI with 4-coils.

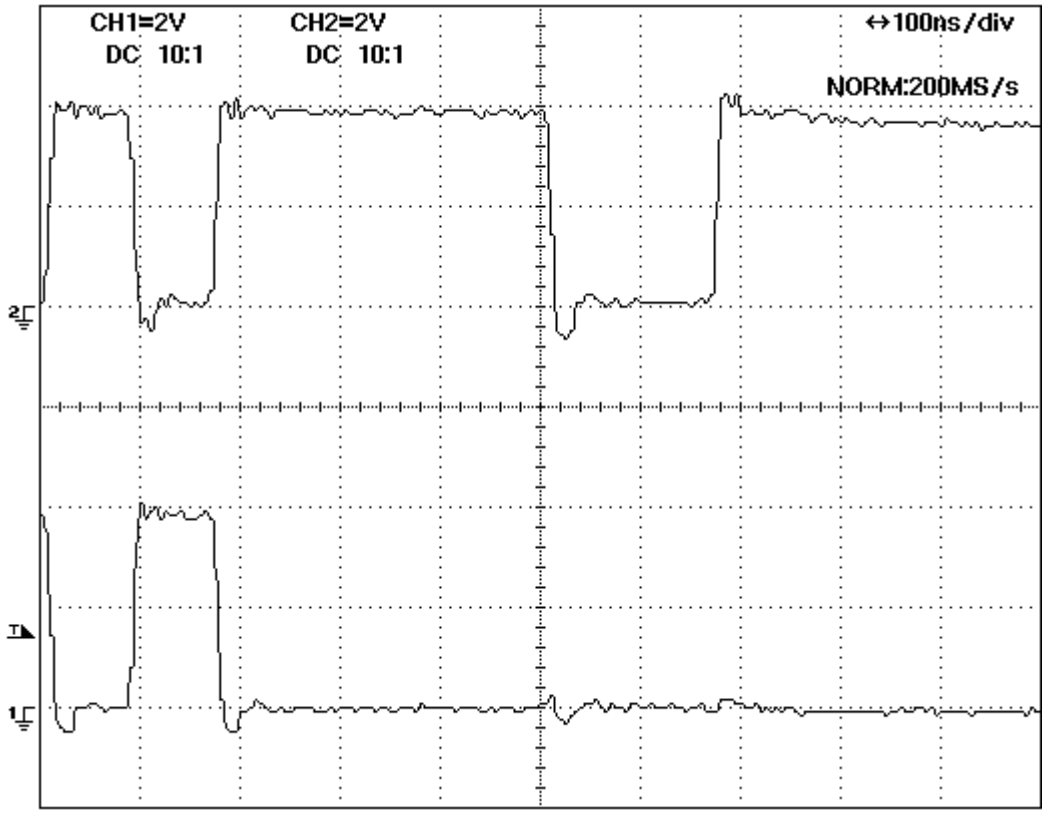



Ch1: Coil Output D+ Ch2: Coil Output D-

**Fig. 10:** USB Data lines when connected via Compaq OHCI with no-coils and no beads.

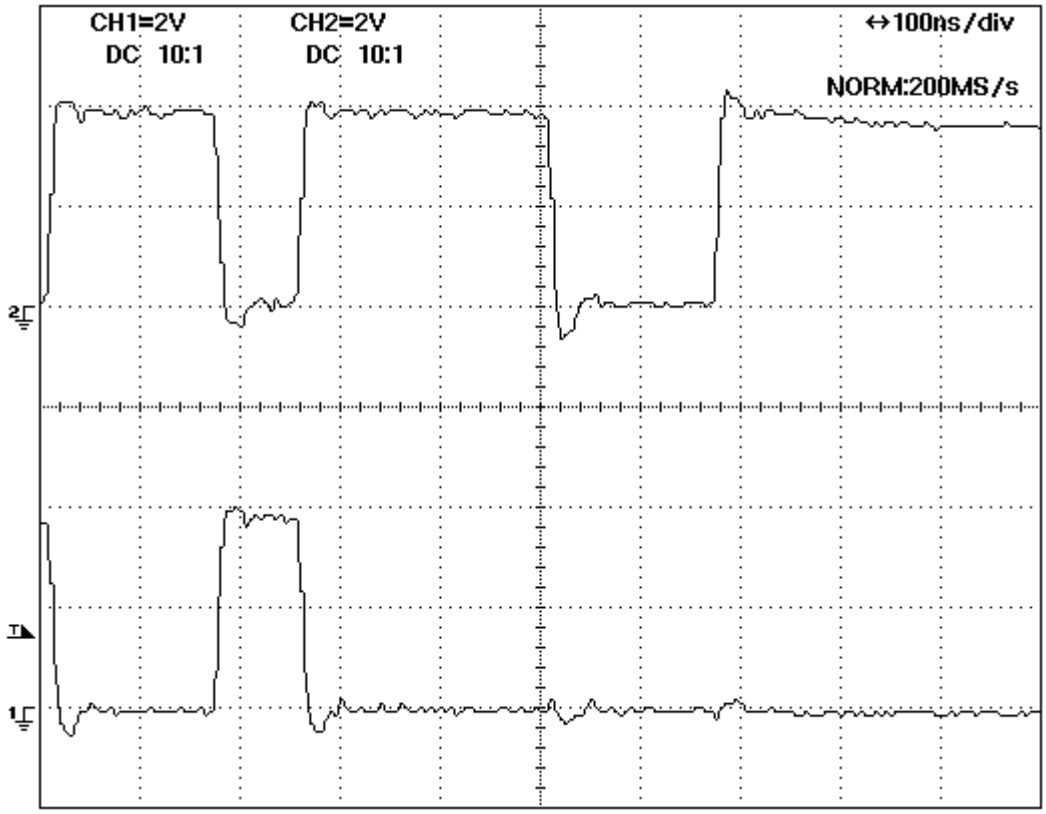
### *4.2- OHCI from CMD*

The CMD OHCI board was also tested and it was found to work correctly for both no-coil and 4-coil configurations. The resulting USB data waveforms for each configuration are shown in Figures 11 and 12. As expected, the waveforms for both configurations were found to be almost identical. Note also that the USB waveforms generated by this board have significantly less overshoot than those generated by the Compaq board.




Ch1: Coil Output D- Ch2: Coil Output D+

**Fig. 11:** USB Data lines when connected via CMD OHCI with 4 coils.

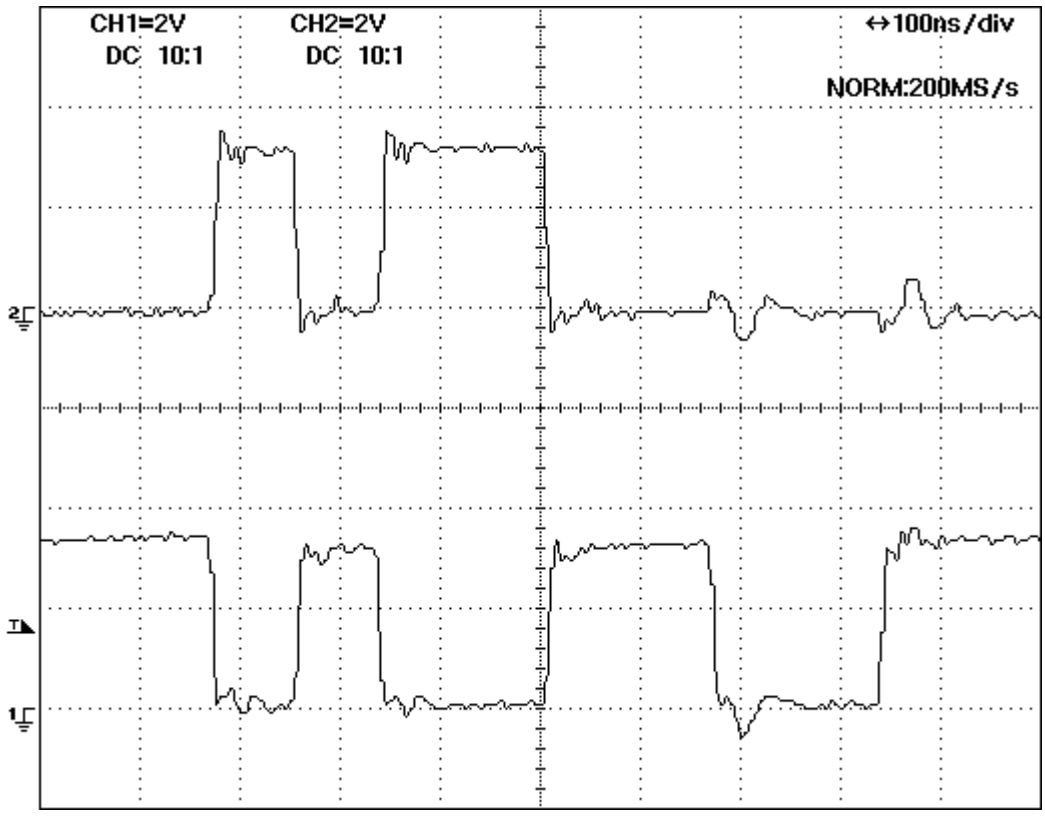



Ch1: Coil Output D- Ch2: Coil Output D+

**Fig. 12:** USB Data lines when connected via CMD OHCI with no-coils and no beads.

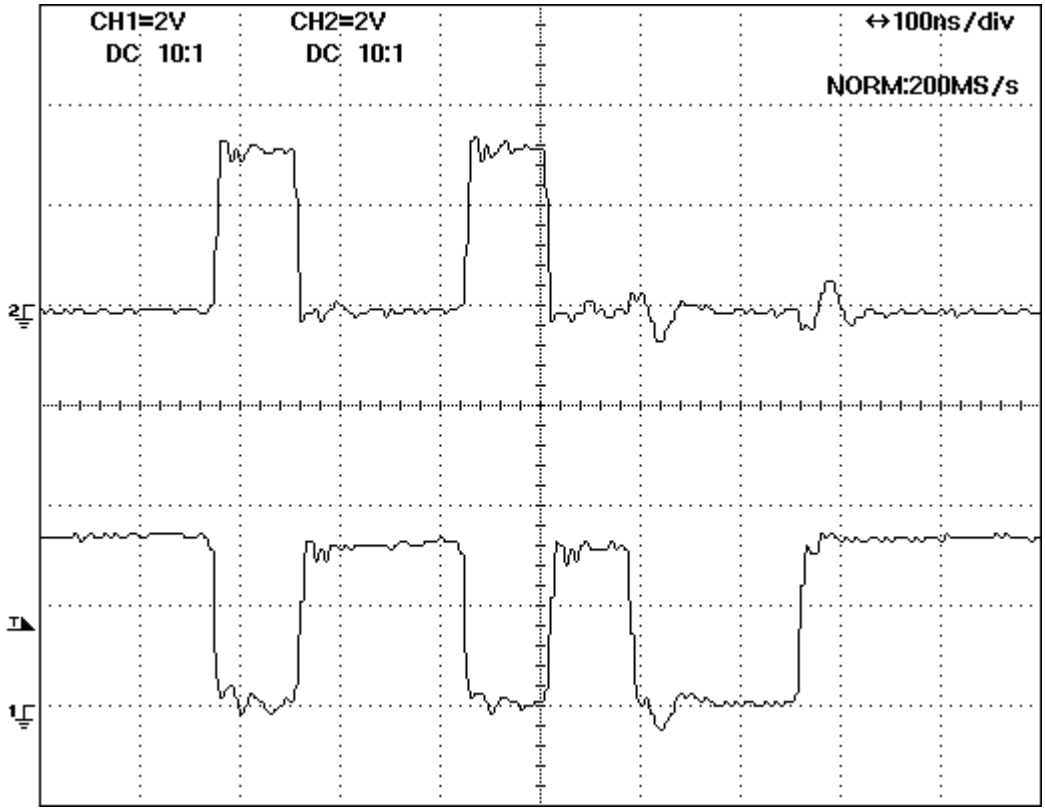
### *4.3- OHCI from Toshiba*

The Toshiba OHCI board was also tested and it was found to work correctly for both no-coil and 4-coil configurations. The resulting USB data waveforms for each configuration are shown in Figures 13 and 14. As expected, the waveforms for both configurations were found to be almost identical. Note that voltage spikes at the start and end of the Single Ended Zero were observed, nevertheless they were not large enough to compromise the performance of the DSS350 speaker.




Ch1: Coil Output D+ Ch2: Coil Output D-

**Fig. 13:** USB Data lines when connected via Toshiba OHCI with 4 coils.

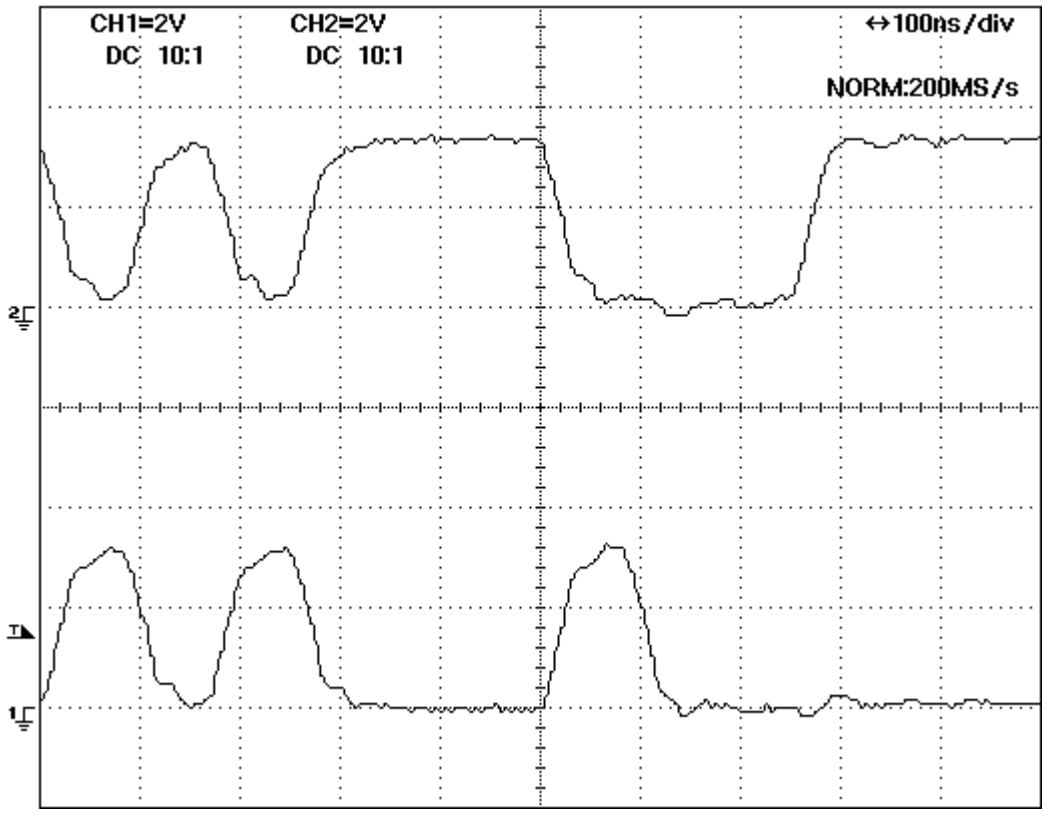



Ch1: Coil Output D+ Ch2: Coil Output D-

**Fig. 14:** USB Data lines when connected via Toshiba OHCI with no coils and no beads.

### *4.4 - OHCI from OPTI*

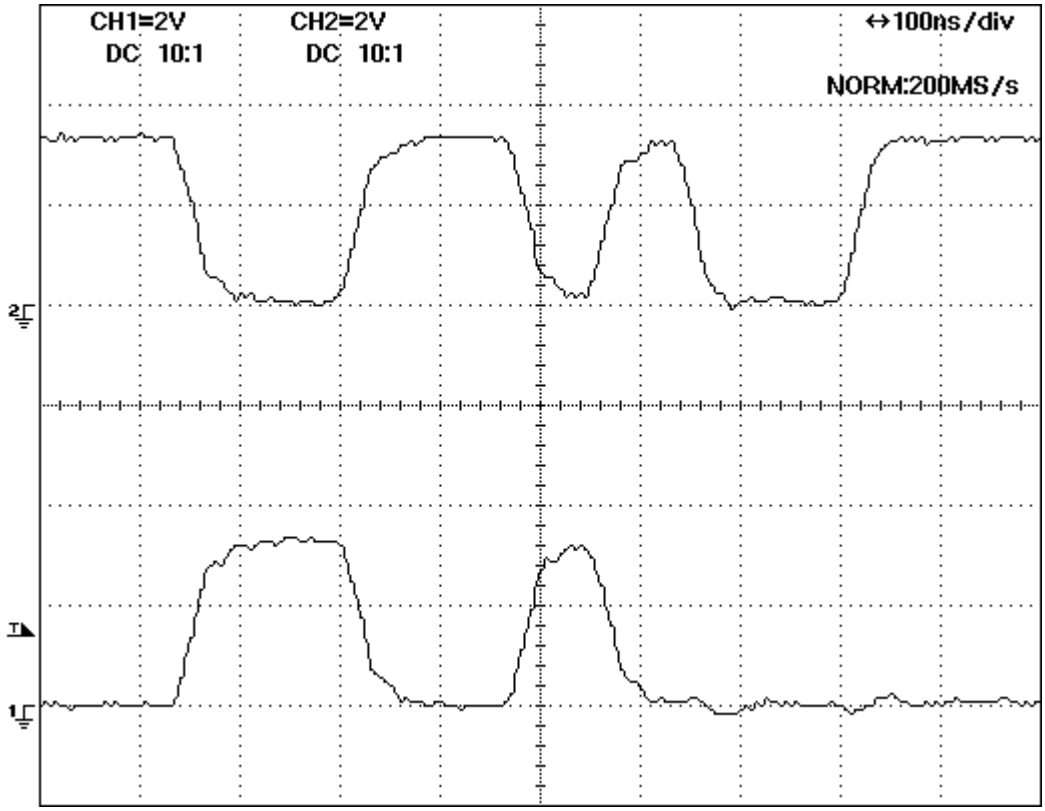
The OPTI OHCI board was also tested, the results obtained for this board are particularly important since this is one of the OHCI to be supported by Microsoft. The USB speaker when connected via this card played music for about 10 seconds and then stopped. This performance occurred for both 4-coil and no-coil configurations. The resulting USB data waveforms for each configuration are shown in Figures 15 and 16. As expected, the waveforms for both configurations were found to be almost identical. Note that the transitions in the output data from this card have very rounded edges compared to the other USB waveforms observed so far. The rise and fall of the times of the USB data were then measured changing the time base of the oscilloscope and they were found to be well above the 20ns specified in USB specifications (Section 7.1.10) for full speed data. This observation is illustrated in Figure 17. These non-USB complying rise and fall times were thought to be the main cause of the problems observed in the performance of this card.




Ch1: Coil Output D- Ch2: Coil Output D+

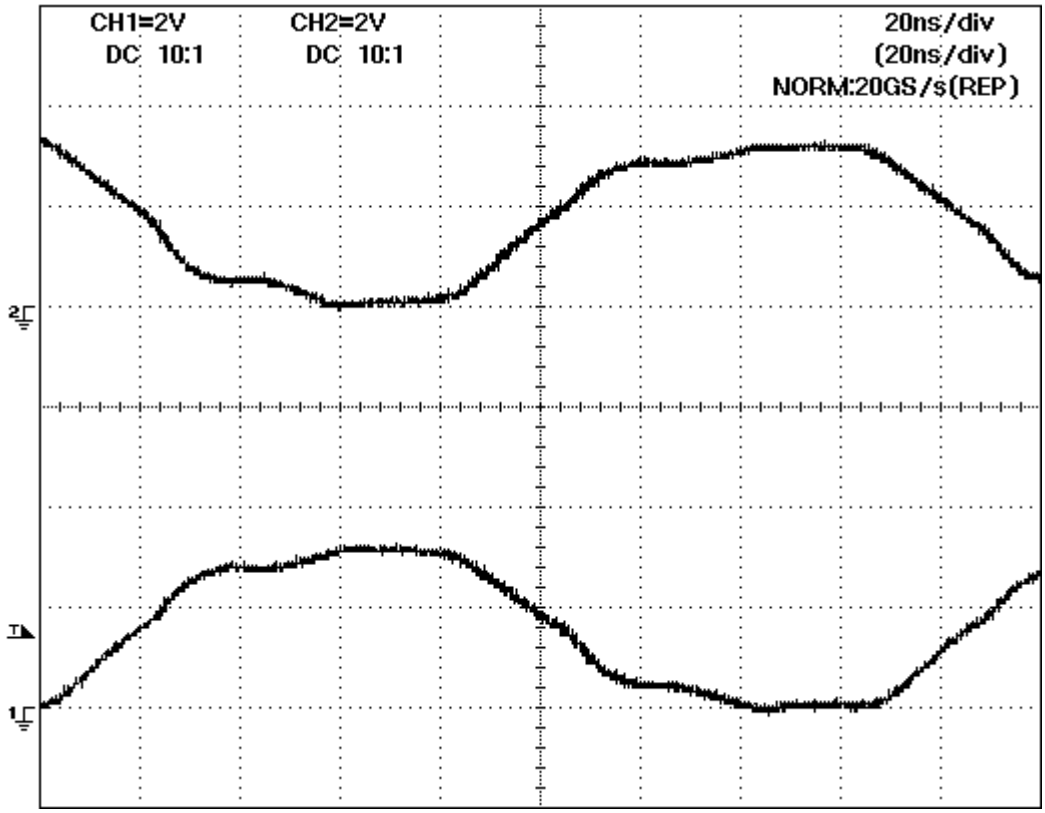
**Fig. 15:** USB Data lines when connected via OPTI OHCI with 4 coils.

By: Javier Lopez and Bruno Putzeys version 1.0 98-04-30




Ch1: Coil Output D- Ch2: Coil Output D+

**Fig. 16:** USB Data lines when connected via OPTI OHCI with no coils and no beads.




Ch1: Coil Output D- Ch2: Coil Output D+

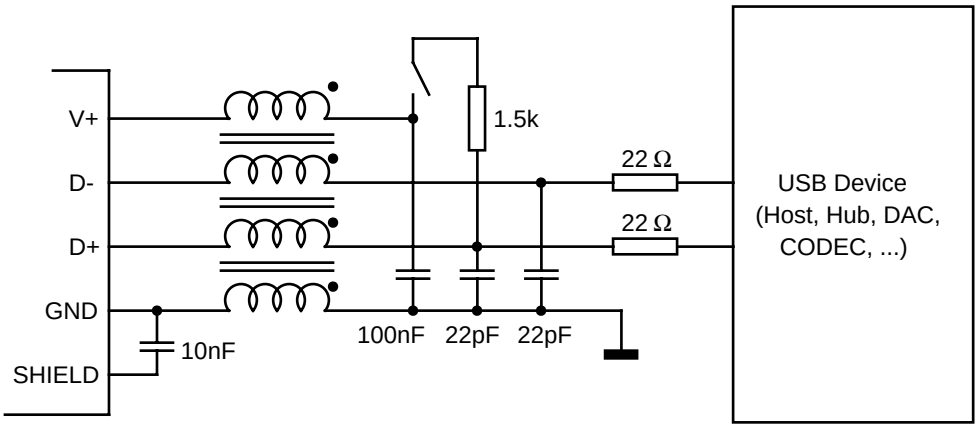
**Fig. 17:** Rise and Fall for USB Data lines connected via OPTI OHCI.

### *4.5 - Other OHCI cards*

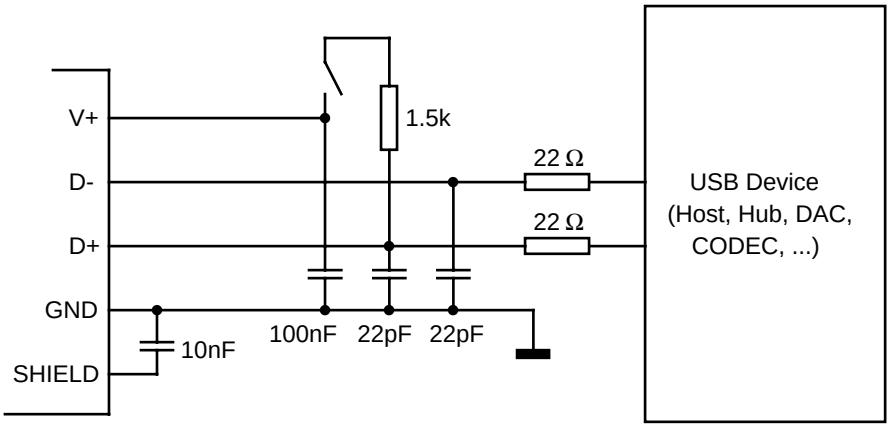
In addition to the 4 OHCI tested and described in the previous sections, two more boards were also tested, a SIS board and a National Semiconductor boards. These 2 boards did not work due to PC crashing every time it attempted to load the software for these drivers. Hence, the USB for these 2 boards could not be investigated.

## *5 – Conclusions and recommended circuit implementations:*

This investigation can be concluded by stating that the 4-coil and no-coil solutions worked equally well for all USB set-ups implemented using the DSS350. These 2 configurations are the only two valid ones, and USB input circuit implementations containing common mode coils in some but not all four USB Lines should not be used. Hence, for future USB applications inductors should not be placed arbitrarily as it has been done in the past, these inductors cause unwanted voltage spikes in the USB Data Lines, as it has been shown in this report, which may result in false transitions. The 2 recommended input circuits are shown below in Figure 18. The 4-coil common mode choke is the safer and preferred solution if you need to rush a certain design into production and the designer does not want to take any chances with EMC. However, the no-coil solution is better and cheaper and it is the preferred solution at the beginning of a project unless major EMC problems are foreseen.




The Safe Option: Preferred if you have to rush out a product and don't want to take any risks for EMC.




The Cheap Option : Preferred at the beginning of a project.

**Fig. 18:** The 2 recommended USB input circuit implementations.

## *6- Annex: Why beads and twofold common-mode coils degrade the signals*

Common mode chokes (CMC's) are intended to, well, "choke" common-mode signals. Usually this is fairly simple to do: if one feeds all lines of a given signal through a common mode coil, the differential signals will pass unharmed, but common-mode currents will be blocked.

The operation is quite simple: differential signals will pass through the windings twice: once as the signal, once as reference current. The nice thing is that those currents will pass the CMC in the opposite direction, which makes the magnetic fields in the core material cancel and hence cancels the induction of the coil.
Common-mode signals on the other hand flow through the 2 windings in the *same* direction, both causing the same magnetic field. As a result, the inductance of the common-mode device will be rather highish, thus blocking the common-mode signal.
The trouble with common-mode signals is that they "view" the cable as a single piece of wire (all circuits connected in parallel), creating an antenna. Equally troublesome is the fact that common-mode currents will convert themselves into differential currents whenever the impedances in the reference and the return are not exactly the same. Given that the reference is normally ground/chassis (very low impedance) and the input impedance is high, one can easily see that the common-mode current can mix in with the wanted signal.
If any of those two problems are present (only if!) and there's no other way to fix it, you might consider placing a CMC.

## *6.1- Application of CMC's in USB circuits.*

Firstly, how does a shielded cable radiate? Only the *shield* can radiate because all other conductors are electrically invisible to the outside world. One of the tested input circuits had a common-mode choke in the signal lines where the power/gnd/shield was connected thru ferrite beads. As a result, the CMC cannot have any discernible effect on radiation.
Secondly, **what does the wanted signal in USB look like**? Basically, it's differential, BUT it was decided to have the end of each packet signalled by a "single ended zero" i.e. by pulling *both* lines low. This makes the common-mode part of the signal half the supply voltage during packet transmission and zero during the single-ended zero. A CMC, accidentally landed in the D+ and D- lines only, will attempt to block/attenuate common-mode spikes and as such, the single-ended zero.
Otherwise put, during the transmission of the single-ended zero, the signal reference is NOT the opposite data line but the ground line, and through decoupling caps also the 5V line. If we replace the two-fold coil by a fourfold one and feed the ground/supply conductors through it, the return current of the two lines will flow back through the device, which will now no longer present any threat to the single-ended zero.

## *Correct use of CMCs in cable connections*

1. Find out which part of a connection is radiating. If there is none, no CMCs are necessary.
2. If the offending line is a signal, find its reference. Otherwise, go to 3.
3. Find *all* signals belonging to that reference.
4. Feed all of these lines through one CMC.

For all but entirely differential connections this algorithm usually yields the complete cable, which is very much the case here.

## *6.2- Signal deterioration due to ferrite beads / chip inductors.*

A number of reviewed USB apps sport ferrite beads in the ground and supply lines, the reasoning probably going that these lines should carry DC only. Unfortunately this is not the case as these lines are acting as the reference for the single-ended zero and hence carry the return current. From the oscillographs (cf. Supra), it can be seen that the effect of the ferrite beads in the supply and ground lines is analogous to that of the two-fold common-mode coil.

Conclusion:

- Make sure there is an EMC problem before acting.
- Use EMI countermeasures carefully because if injudiciously applied, several of them might interfere with the wanted signal. To this end, always ask the question: what is the signal and what is its reference (or return).