

The Open-Source Directly-Heated Triode Electrostatic Headphone Amplifier (OSDEHA)

Matthias Brennwald

THIS DOCUMENT IS UNDER CONSTRUCTION!
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1. OVERVIEW

This document describes an audio amplifier for electrostatic headphones. The design of the amplifier is targeted at DIY builders and is published as open hardware (see Sec. 9).

Electrostatic headphones operate on audio signals characterized by high voltage and low current. This is the domain of vacuum tubes, making them most suitable as drivers for electrostatic headphones. While there exist a number of tube amplifiers for electrostatic headphones, many of these designs do not utilize directly-heated triodes (DHTs), which exhibit outstanding linearity and sound quality.

The OSDEHA uses DHT tubes for its output stage and implements the following design goals:

- The audio output is taken directly from the anodes of the DHT output tubes. There are no transformer or capacitors to transfer the power to the headphones.
- The amplifier input takes balanced input at signal levels of modern audio sources (mostly DACs these days).
- The design prioritizes the quality of audio reproduction and electronic design rather than on low cost.
- The amplifier should be reasonably compact. The power supply unit may be a separate unit to keep the amplifier unit reasonable compact.

The OSDEHA design files, along with supporting documents and data, are available in the OSDEHA file repository.[?]

There is a public discussion thread of the OSDEHA at diyAudio.[?]

2. AMPLIFIER DESIGN

2.1. *Driving Electrostatic Headphones*

Electrostatic headphones operate using three electrodes: two fixed outer electrodes (stators) and a movable central electrode (diaphragm). The diaphragm is biased at a high voltage relative to the stators. The audio signal is applied to the stators in opposite polarities, generating an electric field that controls the movement of the charged diaphragm. For accurate sound reproduction, the electrostatic forces acting on the diaphragm must be proportional to the applied audio signal. To prevent distortion of the audio output, the charge on the diaphragm must remain constant.

The electrical impedance of electrostatic headphones is primarily determined by the capacitance of the two stators, which is typically around 100 pF.[?]

The voltage swing required to drive the stators depends on the headphone sensitivity and the desired sound pressure level. An experiment using various genres of well-recorded music indicated that an undistorted 1.3 kV peak-to-peak swing of the bipolar output is desirable (i.e., 650 V peak-to-peak at each stator).[?] The corresponding current swing measured in this experiment was approximately 4 mA. However, driving the 100 pF load to full output at frequencies up to 20 kHz and beyond necessitates larger peak currents, around 20 mA.[?]



Figure 1: Conceptual layout of the OSDEHA: differential input and gain stage, push-pull DHT output stage.

2.2. Output Stage

Fig. 1 illustrates the conceptual layout of the OSDEHA. The output stage employs two DHTs in a push-pull configuration to deliver the symmetric, bipolar output required to drive electrostatic headphones. For efficient audio power transfer to the headphones, the AC impedance of the anode loads must be much larger than that of the headphones (several $M\Omega$). This cannot be achieved using passive anode-load resistors; instead, active constant-current sources (CCSs) are employed. The CCS loads not only enhance the amplifier's linearity and voltage gain but also suppress ripple and noise from the B+ rails.

The choice of output tube type is dictated by the drive requirements of the headphones, as described in Sec. 2.1. Since the two tubes are connected in series with the headphones, each tube is responsible for half of the total voltage swing. Thus, each tube must handle a swing of ± 325 V at a 20 mA bias. Furthermore, to emphasize the characteristic “DHT sound,” the DHT output stage should contribute as much voltage gain as possible to the overall amplifier gain.

Several DHT tube types were evaluated for the OSDEHA.^{?,?} Specifically:

- The 841/VT-51 tube offers a gain of $30\times$ and can be biased up to 425 V. However, at the operating point required for the OSDEHA, the 841 tends to operate with a positive grid voltage, leading to grid current draw. Additionally, these tubes are relatively scarce.
- The 20B tube is a modern design with a gain of $20\times$ and supports biasing up to approximately 500 V. However, these tubes are quite large (roughly the size of a beer bottle) and are produced only in small quantities by a single manufacturer (Emissionlabs), raising concerns about their long-term availability.
- The family of the 801/801A/VT-62 and 10Y/VT-25 types[?] provide a gain of $8\times$. The 801 can be biased up to 500 V, while the 10Y should not be biased above 450 V. These tubes are available as new-old-stock and from new production.

From a technical perspective, the high gain of the 20B makes it an attractive option. However, due to concerns about the long-term availability of the 20B, the 801/10Y family of tubes is deemed a more practical choice for the OSDEHA design.



Figure 2: Characteristic curves of the 801A DHT, showing a DC bias point at 420 V and 20 mA, with a constant-current load line allowing an anode swing of ± 325 V (blue).



Figure 3: Simplified circuit of the active load (AC-coupled CCS).

Fig. 2 illustrates the characteristic curves measured from the 801A tube (with the 10Y/VT-25 being equivalent) along with the load line of a 20 mA constant-current source (CCS). The anode DC bias is set to 420 V, corresponding to a grid bias of approximately -34 V. This bias point allows for an anode voltage swing of ± 325 V within the tube's linear operating range. The grid voltage remains below $+10$ V, where measured grid current stays well under 1 mA. With the anode voltage approaching ground potential, the B- voltage is set to -420 V and the B+ voltage to 420 V, maintaining symmetry.

Fig. 3 shows the simplified circuit of the CCSs used to load the anodes of the DHT output tubes. This circuit functions as a CCS in the audio/AC domain while providing a fixed voltage in the DC domain. In both cases, the FET Q1 controls the circuit's output to the anode. The depletion-mode FET Q2 drops most of the voltage from B+ and isolates Q1 from any noise or ripple present in the B+ supply.

In the audio/AC domain, the gate of Q1 is connected to the anode through capacitor C. Q1 mirrors any AC variation in the anode voltage from its gate to its source pin. This configuration maintains a constant voltage between the source of Q1 and the DHT anode, thereby ensuring a



Figure 4: Simplified circuit of the input stage.

constant current through R2. If the headphone stator is driven directly by the DHT anode (output 1 in Fig. 3), this current is shared between the DHT and the stator. Consequently, the current flowing through the DHT will exhibit slight variations in response to the AC current consumed by the stator. These variations are typically less than 4 mA,[?] which is significantly smaller than the DC bias current. As a result, the load line seen by the DHT anode will closely resemble the one shown in Fig. 2, although it may not be perfectly flat. Alternatively, the stator can be connected to the μ -output (output 2 in Fig. 3) instead of taking the audio output directly from the DHT anode. In this μ -follower configuration,^{?,?} the stator draws its current directly from Q1 rather than through R2. This restores the constant-current operation of the DHT tube and produces a flat load line as shown in Fig. 2. The value of R2 is typically chosen as a compromise between maximizing the impedance of the CCS load and minimizing the voltage drop (and heat dissipation) across R2.[?]

In the DC domain, the gate of FET Q1 is grounded through R1, fixing the source pin at $-V_{GS,0}$. This arrangement biases the anode at a slightly negative DC voltage determined by $V_{GS,0}$ and the DC voltage drop across R2. As a result, the amplifier outputs maintain a stable DC voltage, effectively compensating for any thermal drift or aging of the DHT tubes.

2.3. Input Stage

The primary function of the input stage is to amplify the balanced input signal (2×3.5 V peak-to-peak) to a level sufficient to drive the DHT grids (2×86 V peak-to-peak). This requires a voltage gain of $86/3.5 = 25\times$.

Following the lines of the output stage, the differential input stage is designed as long-tailed pair (LTP)[?] utilizing tubes with triode characteristics. To maximize the linearity and voltage gain of the LTP, the “tail” is configured as a constant-current source (CCS), as illustrated in Fig. 4.

A triode-connected 6E5P tube provides suitable gain and exhibits very linear amplification.^{?,?} Each 6E5P is biased at 10 mA with an anode-to-cathode voltage of 170 V and a 25 k Ω load resistor, providing more than ± 100 V of anode AC swing (Fig. 5).

The LTP input stage is capacitor-coupled to the grids of the output DHTs. A properly chosen capacitor does not introduce measurable distortion to the audio signal,[?] provided there is no significant current flow across it.[?] To ensure stable biasing, the DHT grids are driven by FETs



Figure 5: Characteristic curves of a triode-connected 6E5P tube, showing a 25 kΩ load line with DC bias at 170 V and 10 mA.



Figure 6: Simplified circuit of the high-voltage power supplies.

configured as source followers. The DC bias voltage for the DHT output tubes is applied to the gates of these FETs, ensuring stable operation even when the DHT grids are driven into grid current.

3. POWER SUPPLIES

3.1. High-Voltage Supplies ($B+$, $B-$, $B2-$)

The amplifier's input and output stages operate on a bipolar high-voltage supply ($B+$ and $B-$ rails). Additionally, the DHT grids require a bias voltage more negative than $B-$, necessitating an additional $B2-$ supply. All three high-voltage supplies utilize the same circuit design to deliver clean and stable voltage outputs (Fig. 6). The circuits are deliberately designed without feedback-based voltage regulation, as such feedback loops are often associated with sound degradation. A full-wave rectifier and smoothing capacitor ($C1$) generate a raw DC voltage. This raw supply feeds a current source that injects a small, constant current into $R1$ and $C1$. Once $C1$ is fully charged after startup, $R1$ develops a constant voltage drop, which serves as a reference mirrored to the voltage output across the $DC+$ and $DC-$ terminals. For the $B+$ supply, the $DC-$ output is referenced to GND, while the $B-$ and $B2-$ supplies have their $DC+$ terminals at GND.

To prevent audio noise during startup and reduce stress on the tubes, the high-voltage supplies are activated only after the tubes have warmed up for a few seconds. This delay is implemented using a relay switch controlled by a timer triggered by the heater supply.

3.2. Diaphragm Bias Voltage

High-performance electrostatic headphones typically require a 580 V DC bias voltage for the diaphragm. The current output of the bias voltage supply is negligible. A charge pump riding on

the B+ rail and its AC supply is used to charge a string of capacitors, with their voltage limited to the intended bias level by a string of Zener diodes in parallel to the capacitors. It is crucial to maintain the *charge* on the diaphragm, rather than the diaphragm voltage. To this end, a high-ohmic current-limiting resistor is inserted in the output of the bias supply.

3.3. Heater Supply for the Input-Stage Tubes

The heaters of the input-stage tubes are powered by a clean DC voltage to prevent crosstalk of hum or noise from the heater supply into the audio signal. This DC supply is implemented using a standard three-pin voltage regulator chip.

3.4. DHT Filament Supply

Like the input-stage heaters, the DHT filaments are powered by DC. However, in DHTs, the filament also serves as the cathode and is part of the audio circuit. During audio playback, a small signal voltage develops across the filament terminals. To prevent the DC filament supply from interfering with this AC signal, it is preferable to control the filament supply current rather than the voltage. This is accomplished using the Coleman Regulator.⁹ The OSDEHA utilizes four Coleman Regulator V9 boards (one per DHT). In each amplifier channel, a single raw DC supply can power a pair of V9 boards.

4. PUTTING THE PIECES TOGETHER

Fig. 7 provides an overview of the various OSDEHA units and their interconnections. The units are distributed across two chassis: one for the power supply and another for the amplifier.

Power-supply chassis:

- IEC mains inlet with a power switch and mains fuses
- Two mains transformers
- Main power-supply board providing stabilized DC voltages for B+, B-, B2-, diaphragm bias, and the heaters of the input-stage tubes
- Two boards supplying raw DC to the Coleman DHT filament regulators

Amplifier chassis:

- Two amplifier main boards (left and right channels)
- Four DHT power tubes (two per channel)
- Four Coleman DHT filament regulators
- Two XLR audio input sockets
- Stereo balanced volume control
- Stax headphone output socket

The two chassis are interconnected by two umbilical cables, U1 and U2. U1 carries the high-voltage, low-current supplies (B+, B-, B2-, GND) and provides the chassis-to-earth connection. U2 carries the low-voltage, high-current supplies for the heaters of the input-stage tubes and the Coleman DHT filament regulators.



Figure 7: Overview of the OSDEHA units and their connections (see text).

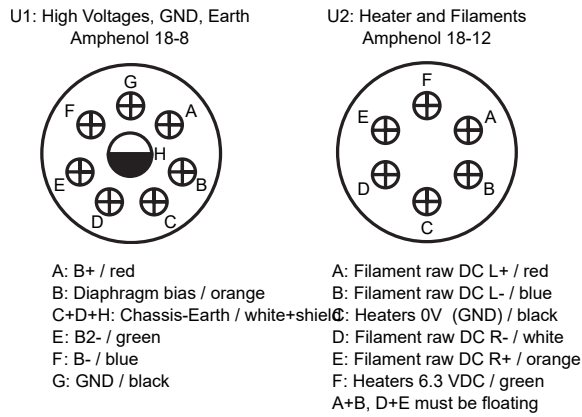


Figure 8: Pinout of the power umbilical connections between the power supply and amplifier chassis.

5. MECHANICAL CONSTRUCTION

HEATSINKS, CHASSIS, ETC.

UMBILICALS BETWEEN PSU AND AMP CHASSIS in Fig. 8.

6. BUILD NOTES, BRING-UP, AND INITIAL ADJUSTMENTS

The process of building, testing, and adjusting the OSDEHA is best carried out step by step, as outlined below. Use a variac to gradually ramp up mains power while bringing up the circuits. It is recommended to build, install, and fully test one amplifier board before proceeding with the second. Before working on the circuits, always ensure that no dangerous voltages remain present (e.g., all capacitors are discharged, and the mains cable is disconnected).

6.1. Power Supply

- Assemble the power-supply chassis and boards. Install the boards, sockets, and transformers in the power-supply chassis. Connect the primary windings of the transformers to the mains inlet and power switch in the chassis. Connect the power supply outputs to the umbilical sockets.
- Confirm proper connection of all metal parts of the power-supply chassis to mains earth.
- Connect the transformer secondaries for the heater supply. Gradually ramp up mains power using the variac and confirm that the heater supply functions as expected. Verify the operation of the high-voltage delay relay.
- Connect the transformer secondaries for the DHT raw-DC filament supplies. Gradually ramp up the variac to confirm that the raw-DC supplies function correctly.
- Connect the transformer secondaries for the high-voltage supplies and install dummy resistors at their outputs. Gradually ramp up the variac, confirm and adjust the high-voltage output levels as needed. Verify the diaphragm bias voltage output (note: the internal resistance of the voltmeter will load the bias output, resulting in a lower voltage reading). Remove the dummy resistors from the high-voltage supplies.



Figure 9: Circuit to determine the sense-resistor value R_s that yields the desired CCS current for a given DN2540 part. Adjust the R_s value until the voltage drop V_x across the $100\ \Omega$ resistor corresponds to the desired current.

6.2. Amplifier Input Stage

- Determine the CCS sense-resistor values that yield the targeted bias currents for the CCSs with the specific DN2540 parts used in the input LTP tail and in the DHT grid drivers (Fig. 9).
- Assemble the amplifier chassis, boards, and Coleman filament regulators. Install the boards and sockets in the amplifier chassis. Install the input-stage tubes, but do *not* install the DHT tubes of the output stage yet. Do *not* yet wire the umbilical sockets to the boards.
- Connect the umbilical cables between the power supply and the amplifier. Connect the amplifier chassis to the earth pin of the umbilical socket. Confirm the connection of all metal parts of the amplifier chassis to the power-supply chassis and mains earth. Make sure the XLR-1 pins are connected to the chassis.
- Connect the heater supply from the umbilical socket to the amplifier board. Gradually ramp up the variac and confirm proper functioning of the heaters in the input-stage tubes.
- Connect the high-voltage supplies and GND from the umbilical socket to the amplifier board. Gradually ramp up the variac and confirm the correct DC bias of the input-stage tubes (plate voltages and currents) and the DC bias currents of the buffer stages.
- Connect the audio inputs from the XLR sockets to the amplifier. Apply an AC test signal to the XLR sockets and trace the signal path through the circuit, verifying correct output from the buffer stage.

6.3. Amplifier Output Stage

- With the output tubes still not installed in the amplifier, adjust the DC grid bias of the output tubes to the most negative value.
- Disconnect the high-voltage supplies from the amplifier board, connect the DHT filament supply from the umbilical socket to the amplifier, and install the DHT output tubes. Gradually ramp up the variac and adjust the filament voltage to the target value. Allow the tubes to warm up and readjust the filament voltage as needed.
- Reconnect the high-voltage supplies to the amplifier board and gradually ramp up the variac. Monitor the DC bias current of each output tube by measuring the voltage across the mu-resistors. Adjust the DC grid bias until the desired DC bias points are attained. Allow the amplifier to warm up and readjust the DC bias as necessary. Also monitor the filament voltages during warmup and adjust if needed.
- Apply an AC test signal to the amplifier input and verify correct output from the amplifier.

7. SPECIFICATIONS AND TEST RESULTS

TESTS AND MEASUREMENTS

OUTPUT BEFORE CLIPPING

FREQUENCY RESPONSE

DISTORTION MEASUREMENTS (THD, IMD, SPECTRA)

8. PARTS LIST

The details of most electronic components used in the OSDEHA circuits (tubes, semiconductors, resistors, capacitors) are provided in the KiCad files located in the `kicad/` directory.[?] Additional parts, such as chassis, mounting hardware, and connectors, are listed below.

Part Description	Number	Manufacturer	MPN and Details
UX4 tube sockets	4	(various)	sub-chassis mount
Noval tube sockets	4	(various)	PCB mount
Stepped attenuator	1	Goldpoint	4 channels, 10 k Ω per channel, 47 positions
Volume knob	1	Custom made	59 mm diameter, for 6 mm shaft
Heatsinks 300×100×40 mm	2	Fischer	SK 56 100 SA
Amplifier front panel	1	Front Panel Express	file OSDEHA_AMP_front.fpd
Amplifier top panel	1	Front Panel Express	file OSDEHA_AMP_top.fpd
Amplifier rear panel	1	Front Panel Express	file OSDEHA_AMP_rear.fpd
Amplifier bottom panel	1	Front Panel Express	file OSDEHA_AMP_bottom.fpd
Amplifier DHT subchassis panel	1	Front Panel Express	file OSDEHA_AMP_subchassis.fpd
Power supply front panel	1	Front Panel Express	
Power supply top panel	1	Front Panel Express	
Power supply rear panel	1	Front Panel Express	
Power supply bottom panel	1	Front Panel Express	
Chassis panel joints		n/a	10×10 mm aluminium rods
Chassis feet	8	(various)	
XLR input socket	2	Neutrik	NC3FD-L-B-1, 3 contacts, female
IEC mains inlet	1	Schurter	KM00.1105.11
IEC mains inlet fuse holder	1	Schurter	4301.1401
Mains fuse	2		5×20 mm
Power supply outlet socket (HV)	1	Amphenol	MS3102E18-8S
Amplifier power socket (HV)	1	Amphenol	MS3102E18-8P
Umbilical connector (HV/PSU)	1	Amphenol	MS3106E18-8P
Umbilical connector (HV/AMP)	1	Amphenol	MS3106E18-8S
Power supply outlet socket (F+H)	1	Amphenol	MS3102E18-12S
Amplifier power socket (F+H)	1	Amphenol	MS3102E18-12P
Umbilical connector (F+H/PSU)	1	Amphenol	MS3106E18-12P
Umbilical connector (F+H/AMP)	1	Amphenol	MS3106E18-12S
Umbilical wires	2	Lapp	301606S
Power indicator LEDs	2	Vishay	VLHW5100 (or other 5 mm white LED)
Power indicator LEDs, resistors	2	Vishay	CMF55200R (for connection to 6.3 V heaters)
Screw terminals	4	Phoenix Contact	1729128 (Filemant regulator boards)
Test sockets for DHT filaments	8	Alltech	975455700
Standoffs, metal, M3×8 mm	20	Hasler	83.2220.03008 / PCBs
Standoffs, metal, M3×30 mm	6	Hasler	83.2220.03030 / Subchassis
Allen screws M4×12 mm	?	Hasler	83.1215.04012 / Panels to chassis joints and heatsink
Headless screw M4×16 mm	?	Hasler	83.1705.04016 / Front panel to heatsink
Allen screws M4×18 mm	?	Hasler	83.1215.04018 / Chassis joints to heatsinks
Allen screws M4×12 mm, flat head	20	Hasler	83.1270.04012 / Top and rear panel
Allen screws M3×5 mm	?	Hasler	83.1215.03005 / PCBs to standoffs
Allen screws M3×5 mm	8	Hasler	83.1215.03005 / DHT sockets to subchassis
Allen screws M3×6 mm	?	Hasler	83.1215.03006 / Standoffs to bottom panel
Allen screws M3×8 mm	14	Hasler	83.1215.03008 / Transistors to heatsinks
Shoulder washers, for TO-220	?	Essentra	10SC004004, insulator washer
Shoulder washers, for TO-247	?	???	???, insulator washer
Heat spreader, for TO-220	?	T-Global	XL25W-TO220-18.5-12-1
Heat spreader, for TO-247	?	T-Global	XL25W-TO247-22-17-1
KK-396 pigtail cable, 2 pin	?	Molex	219665-1024
KK-396 pigtail cable, 3 pin	?	Molex	219665-1034
KK-396 pigtail cable, 4 pin	?	Molex	219665-1044

9. LICENSE INFORMATION

Copyright Matthias Brennwald 2024.

The OSDEHA is Open Hardware and is licensed under the CERN-OHL-S v2 or any later version.

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Source location: <https://github.com/mbrennwa/OSDEHA>

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