Behavior Research Methods
2007, 39 (1), 118-122

A high-sensitivity drinkometer circuit with 60-Hz filtering

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This article describes a drinkometer circuit designed to (1) detect licks even if the resistance of the skin on the animal's feet becomes quite high due to low humidity, (2) automatically adjust its triggering threshold and increase its gain so that it will continue to detect licks when the water delivery spout is partially shorted to ground by high ambient humidity, (3) reject 60-Hz signals so they will not be treated as rapid licks by the data-recording system, and (4) tolerate the high voltages that can occur if the subject receives an electric shock while drinking. This lickometer will be especially useful in situations where it is not practical to monitor for possible signal failure due to high or low humidity, or where 60-Hz artifacts may contaminate the signal provided to a recording computer.

Since Hill and Stellar (1951) published the first drinkometer circuit, most electrical lick-sensing circuits have applied a voltage to the drinking spout through a resistor; they detect voltage reductions that occur when the animal's tongue touches the spout, which grounds the spout through the animal's feet. Such drinkometer circuits have several limitations, including: (1) During the winter, when ambient humidity of the air is very low, the resistance between the animal's feet and the cage floor can become great enough that the signal produced when the animal's tongue touches the spout is too weak to be detected. (2) During months when ambient humidity is high, the voltage applied to the spout may be partially shorted to ground by moisture paths on the hardware that supports the spout; this reduces the steady-state voltage on the spout, making the voltage changes induced by tongue contacts undetectable. (3) Sixty-Hz signals may be electrostatically induced on the spout, and these signals may be treated by computer circuits as rapid licking (i.e., 60 licks/sec). This problem has actually gotten worse as a result of advances in technology. In old circuits in which lick-induced voltage changes were amplified and applied to a relay coil, the mechanical inertia of the relay armature provided a desirable insensitivity to 60-Hz signals. In modern circuits, the relay is usually eliminated, and a logic signal (including any 60-Hz artifact) is fed directly to a computer interface, which must then use digital filtering algorithms to distinguish the lick-induced signals from any 60-Hz artifact. (4) High voltages employed to shock the animal may damage the circuit. (5) The current that passes through the tongue may be detected by the animal, or it may alter the taste of the fluid, thereby changing the rate of licking (Weijnen, 1977).

Here we describe a circuit designed to ameliorate the first four of these problems. The circuit is sensitive to voltage reductions at the spout as small as 1%–2% and hence can detect licking even when the resistance between the ground and the animal's feet is quite high. If spout voltage is reduced by leakage, the circuit automatically adjusts its triggering threshold and increases its gain so that it can continue to detect licks. A series of resistor–capacitor (R–C) circuits comprise a six-stage, low-pass filter that attenuates 60-Hz signals by about 98%. A subsequent digital switch turns off the circuit if a burst of 60 Hz passes through the low-pass filter. Finally, the circuit can tolerate the currents that may occur if high voltage footshock is applied to the subject.

CIRCUIT DESCRIPTION

Referring to Figure 1, the circuit composed of resistor R14 and Zener diodes D3 and D5 produces a 16-VDC signal that is coupled through R7 and R1 to the drinking tube spout (input), where it can be shorted to ground by the animal's tongue. Resistors R2, R3, R4, R5, R6, and R13 in combination with capacitors C1, C2, C3, C4, C5, and C6 comprise a six-stage, low-pass filter that attenuates 60-Hz signals by about 98%. Operational amplifiers Amp 1 and Amp 2 function as voltage followers, with the result that the voltage applied to pin 13 of Amp 3 is equal to the average voltage at the input (with high-frequency components removed).

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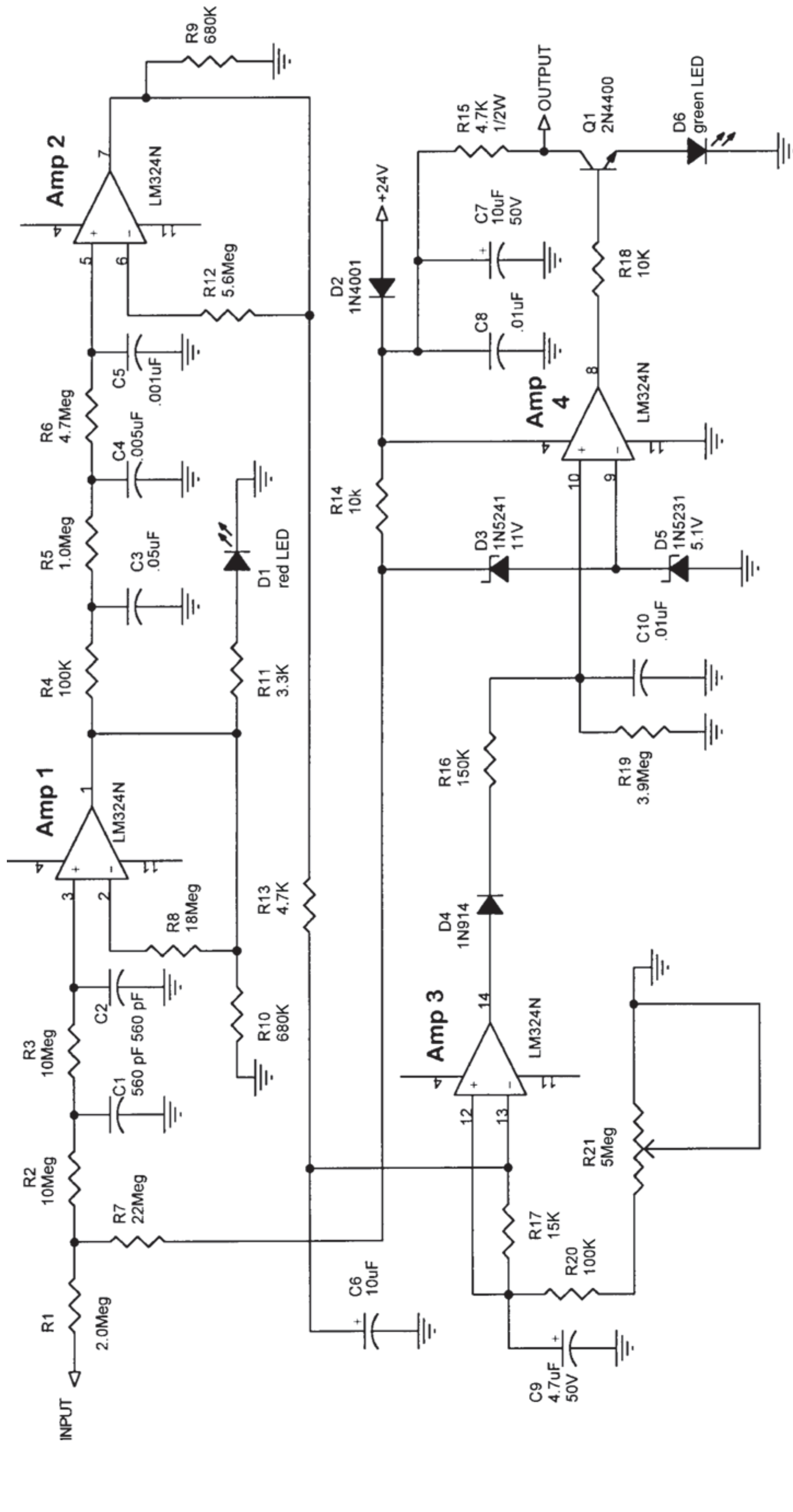

Figure 1. Schematic diagram of the drinkometer.

The components associated with the inputs to Amp 3 provide the most important properties of the circuit because they automatically adjust the triggering level to 1% below the average input voltage. At steady state, when licks are not occurring, the voltage at pin 13 of Amp 3 is +16 V (the same as the voltage at the spout). If R21 is set to 1.4 MΩ, resistors R17, R20, and R21 act as voltage dividers, and they charge C9 to a voltage about 1% lower than the average voltage at pin 13. The voltage across C9 is also applied to pin 12 of Amp 3 and, because the voltage at pin 13 is 1% higher than the voltage at pin 12, the output voltage at pin 14 is low.

When a lick occurs, the voltage at the spout shifts negatively, and the same shift (with its leading edge rounded by the filter capacitors) occurs at pin 13 of Amp 3, forcing the voltage at pin 13 below the voltage still maintained at pin 12 by C9. This causes the output voltage at pin 14 to switch high until the lick terminates or the voltage across C9 decays down to its new asymptote (time constant = 70 msec).

In low-humidity environments, licks can be detected as long as the resistance of the path through the animal's feet does not rise above 2,200 MΩ (100 × R7). In high-humidity environments, when leakage paths reduce the resting voltage on the spout, the circuit continues to detect licks with leakage resistances from the input to ground as low as 1 MΩ. Under these conditions, voltage at the spout approximates 0.6 V and the threshold for lick detection is about 3% below this voltage.

Prior to Amp 3, the circuit operates as a linear analog circuit. Subsequent stages of the circuit, however, process digital signals. Diode D4 in combination with R16, R19, C10, and Amp 4 act as a switch that interrupts signal flow if pulses occur more frequently than 20 Hz. A normal series of tongue contacts with the spout results in a series of +22 V pulses at pin 14 of Amp 3. D4 and C10 comprise a peak detector for these pulses, with R19 functioning to bleed C10 and gradually remove the charge that is placed on C10 whenever the rat's tongue touches the spout. Once a tongue contact has produced a positive voltage at pin 14 of Amp 3, the voltage on C10 is driven above +5 VDC, which causes the output of Amp 4 to swing positive, since the voltage at pin 10 of Amp 4 is compared with the 5 VDC maintained at pin 9 by Zener diode D5. After the lick terminates, the voltage at pin 10 decays exponentially toward ground, passing 5 VDC after about 25 msec, at which point the output of Amp 4 turns off. If a 60-Hz train of pulses reaches the output of Amp 3, pin 14 of Amp 3 will be positive during about half of each 16.6-msec interval, and the output of Amp 4 will be turned on continuously. After the 60-Hz artifact terminates, normal detection of licks will resume. The circuit functions to block short bursts of 60-Hz artifact that might occur while the animal receives footshock.

Resistor R18 drives transistor Q1, which provides an output suitable for many data-recording devices. Light-emitting diode (LED) D6 allows visual observation of the output signal.

DISCUSSION

The major advantages of the circuit described here are its low-pass filtering and its self-adjusting gain and triggering levels. The filtering allows the circuit to provide an artifact-free signal to a recording computer even in environments that contain significant 60-Hz sources. Automatic adjustment of gain and triggering levels makes the circuit unusually capable of dealing with the partial short circuiting of the spout that can occur in high-humidity environments. This gives the unit an advantage in conditions in which constant monitoring for possible humidity-induced signal failure is not feasible—for instance, during 24-h recording.

As every circuit design involves trade-offs, no drinkometer can be optimal for every application. For example, the circuit filters the signal, delays it by several milliseconds, and does not report lick durations, making this circuit unsuitable for experiments that require a microanalysis of lick lengths or interlick intervals. Also, the magnitude of the current that passes through the animal's tongue (0.7 μA) is not low enough for all applications. Reduction of the tongue current can be achieved by increasing R7, but this change would increase sensitivity to 60-Hz interference. If very low tongue currents are required, alternative circuits that use currents that are an order of magnitude lower than those used by the present circuit are available (see, e.g., Taylor-Burds, Westburg, Wifall, & Delay, 2004, or e-mail: ross@diloginstruments.com), and 60 Hz can be controlled by using electrostatic shielding. Weijnen (1977, 1989, 1998) has provided helpful descriptions of many of the factors that should be considered when selecting a drinkometer circuit.

AUTHOR NOTE

This research was supported in part by National Institute on Drug Abuse Grants DA-02403 and DA-04275 and National Institute on Alcohol Abuse and Alcoholism Grant AA-09358 to D.A.O. While supplies last, sample circuit boards are available from D.A.O. Correspondence concerning this article should be addressed to D. A. Overton, Psychology Department, Weiss Hall, Temple University, 1701 N. 13th Street, Philadelphia, PA 19122 (e-mail: doverton@temple.edu).

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APPENDIX
Additional Details of Circuit Operation

When the spout is shunted to ground by moisture paths, R1 causes the voltage at pin 3 of Amp 1 to be 1.3 V higher than the voltage at the input and hence within the linear operating range of the amplifier.

When the input is open circuited, the 60-Hz hum signal at pin 3 of Amp 1 should be no larger than 14 V peak to peak; this signal can be measured at pin 1 of Amp 1. If a 60-Hz signal larger than this is present at pin 1, then the peaks will be clipped, which will degrade circuit operation.

LED D1, driven by R11, provides a visual indication of the average DC voltage at the drinking spout. If D1 is not illuminated, then the spout is substantially shorted to ground either by the animal or by leakage currents through moisture pathways on the surface of the hardware that supports the spout.

R8 has a value approximately equal to the sum of R2 and R3 and, due to the input current at pin 2, provides a voltage offset at pin 2 equal to the voltage offset at pin 3 that is produced by passage of input current through R2 and R3. The condition under which it is most critical to equalize these input-offsetting voltages occurs when moisture paths shunt the spout voltage to ground, which causes voltages in the first two stages of the circuit to be close to zero. R10 provides a load to ground for Amp 1, allowing it to act as a current source even when LED D1 turns off. Additionally, R10 sinks the input current coming out of pin 5 of Amp 2.

Operation of Amp 2 is analogous to that of Amp 1. R9 insures that pin 7 can operate as a current source by sinking the input current from pin 13 of Amp 3. R12 has a value slightly less than the sum of R4, R5, and R6 and compensates for the voltage drop across those resistors produced by the input current to pin 5 of Amp 2.

The sensitivity of the circuit is determined by the values of R17, R20, and R21. Minimum sensitivity will be achieved by setting R21 to 0 Ω, under which circumstance a 7%–10% reduction in voltage at the spout is required to switch the output of Amp 3. Setting R21 to 1.4 MΩ will allow a 1% reduction in spout voltage to switch the output of Amp 3. This sensitivity is greater than that required under normal operating conditions, when a wet tongue and moderately moist feet may produce a 90% reduction in voltage whenever the animal's tongue touches the spout. However, the high sensitivity is useful if the animal's feet are very dry, in which case the reduction in voltage at the spout may be less than 5%. Further increases in R21 will further increase gain, but such increases typically make the circuit unacceptably noisy. If 60-Hz interference is very great, it may be necessary to decrease the size of R20 below 100 kΩ so that sensitivity can be set below 7%–10%.

In the digital stage, R16 prevents very brief spikes from charging C10. Values for R16, R19, and C10 can be adjusted to vary the delay before another pulse is detected.

R18 and Q1 provide an open collector output that can pull down the input voltage of an interface or operate a relay. Q1 can be an NPN transistor that will sink about 0.5 A. However, if currents in excess of 100 mA are to be sunk by this transistor, R18 should be reduced in size in order to fully turn on Q1. If a relay is to be driven, then LED D6 can be placed in series with R15 so that the relay coil current does not pass through D6. In many situations, it would be preferable to attach the top end of R15 to the positive power supply of the next circuit instead of having it draw current from the drinkometer's power supply. If the output of the drinkometer circuit is to drive a TTL interface, R15 can be 1,000 Ω and should be attached to +4 VDC, and D6 should be removed. The interface or computer circuit that monitors the output of the drinkometer circuit should count the number of pulse onsets but should not treat the continuous presence of a positive voltage at pin 8 of Amp 4 as a series of licks.

The circuit requires a 24 VDC regulated power supply with no more than 0.1-V ripple or voltage variation. Because negative transients in the power supply voltage significantly reduce the output signals from Amp 1 and Amp 2, such transients will produce artifactual outputs. Hence the power supply for the drinkometer circuit should not be used to drive large intermittent loads such as solenoids. C7 and C8 remove spikes from the +24 VDC supply voltage where it is applied to pin 4 of the amplifier chip; C8 should be mounted close to pins 4 and 11 of the chip. D2 prevents the circuit from being destroyed if the supply voltage polarity is reversed.

All components are inexpensive and widely available. The LM324 operational amplifier was selected because it has moderately good performance specifications, provides all four required op-amps in a single chip, and can operate from a single power supply voltage. C6 and C9 should be moderately high quality (i.e., tantalum) electrolytics. Resistors R11, R15, and R21 should be rated 1/4 W and may be 10% tolerance. All other resistors may be 1/8 W and should have 5% tolerance. D2 may be a silicon diode such as 1N4001. The total cost of components in the circuit can be as low as $30. Suitable printed circuit boards can be custom fabricated for $10 to $15 each if a large number is ordered. To date, the circuit has been used in two applications involving 24 circuits and has performed as intended.

The biggest challenge in circuit board design is to minimize the coupling of spikes from the digital output stages (after D4) back to the analog stages. This can occur both electrostatically and because of transients induced in the power supply voltage. Electrostatic feedback can be reduced by physically separating the components and wires associated with the analog circuits from those associated with the digital circuits and by using grounded lands on the circuit board to provide shielding. Because of the high-impedance linear circuits in this device, the entire circuit board should be mounted inside a shielded box so that high-impedance portions of the circuit, such as pin 3 of Amp 1, do not directly pick up 60 Hz, radio station signals, and so forth.

The circuit board should be close to the drinking spout. Since shielded wire can have a capacitance of 100 pF/m, the animal may detect the current pulse that occurs when the tongue touches the spout and discharges the

APPENDIX (Continued)

capacitance of the wire (Weijnen, 1977). One method to minimize this effect is to place R1, R2, and R7 near the spout with the capacitance of the shielded cable serving as part or all of C1. Since most 75-Ω coax antenna wire has a capacitance of about 65 pF/m, this will allow cable lengths up to 8 m.

Finally, certain sections of the circuit can be deleted if they are not required. If transient high-intensity bursts of 60 Hz are not expected, then the components between Amp 3 and Amp 4 can be omitted. If steady-state 60 Hz is not present, then part or all of the R–C low-pass filters can be omitted. If both of these changes are made, then the circuit output will accurately indicate each lick's time of onset and duration, thus removing one of the limitations that is present when the complete circuit is used.

(Manuscript received September 23, 2005;
revision accepted for publication November 11, 2005.)