Hartshorn-Coil Drive

The TeachSpin SIM called 'Hartshorn-Coil Drive' is an electronic module which supports the operation of a Hartshorn coil, a specialized form of transformer. It was designed for use with TeachSpin's Magnetic Susceptibility experiment, which in turn is part of its CMP or Condensed-Matter Physics line. This SIM serves to excite the primary coil of that transformer, and it also provides a 'nulling' or balance output useful for the processing the secondary-coil output of the Hartshorn transformer.

Features:

This SIM requires power from a SIM mainframe or 'crate' (or from TeachSpin's substitute power supply), and it derives all its power from that supply. This SIM also assumes sine-wave audio-frequency drive from an external oscillator.

This SIM provides for the excitation of a floating and inductive load, represented by the primary coil of a 'Hartshorn transformer'.

This SIM includes a V-to-I converter, thus giving a primary-coil current which scales linearly and predictably with the audio-waveform drive of the SIM.

The SIM also provides an auxiliary sinusoidal low-level 'balance' output, of the same frequency as the coil drive; this output permits independent control of the amplitudes of the in-phase, and the quadrature-phase, components of the balance-output signal.

The SIM permits the use of drive frequencies in the range 50 Hz – 5 kHz.

Layout:

Front panel features:

BNC Osc. In connector: this input accepts an a.c. voltage waveform, of frequency in the range 50 Hz to 5 kHz, of amplitude up to 2.2 V. This voltage waveform controls what the current-waveform in the external load will be, according to $i(t) = V_{osc}(t)/10.\ \Omega$.

BNC Curr. Mon. connector: this output provides a ground-referenced output waveform, which reflects the actual load-current achieved, given by $V_{mon}(\mathrm{t}) = i(t) \times 1.0\ \Omega$.

Other front-panel controls refer *only* to the balance output:

> Frequency Band, kHz: this 4-position rotary switch can be set to accommodate the excitation frequency chosen for the Hartshorn coil, in one of four 'bands' in frequency.
>
> In-Phase and Quadrature controls: these center-zero 1-turn dials permit independent control of the in-phase, and the quadrature, components of the balance waveform that the SIM can create.

Attenuation: this 3-position toggle switch can be used further to attenuate the balance output, by use of its ÷1/÷100/÷10 settings.

Rear panel features:

Binding posts TO LOAD: Red and black banana-plug connection points, for connections to the (floating) primary coil of the Hartshorn transformer.

BNC Balance Out connector: the auxiliary voltage output, an attenuated version of the sum of the chosen amplitudes of the two quadratures of the Curr. Mon. output.

Operation:

This SIM provides the electronics that enable the a.c. excitation of the primary coil of a Hartshorn transformer, or some other floating load. The assumption is that an external oscillator, set to an operating frequency f, sends to the SIM a sinusoidal input waveform of the form $V_{\mathrm{osc}}(t) = A \cos(2\pi f t)$. The amplitude A may be chosen in the range zero to 2.2 V.

The main (rear-panel banana-connector) TO LOAD output of the SIM is a bipolar current waveform, a sinusoidal current whose current-amplitude is $A/10\ \Omega$, and whose waveform is $i(t) = (A/10\ \Omega) \cos(2\pi f t)$. The maximal current-amplitude available is 220 mA. Note that the amplitude of the load current is independent of the value of, or in changes to, the resistance, or the inductive reactance, of the load. The voltage-compliance of the output is about ±10 V.

The Curr. Mon. output is a ground-referenced voltage output reflecting the actual current waveform $i(t)$ achieved through the load, with the scaling factor $V_{\mathrm{mon}}(\mathrm{t}) = i(t) \times 1.0\ \Omega$. In particular, this monitor-output is accurately in phase with the instantaneous current passing through the load.

Note that there are no adjustments required (or possible) in this mapping from the input $V_{\mathrm{osc}}(t)$ to the output $i(t)$. All of the front-panel adjustments affect *only* the back-panel low-level balance-voltage output.

The algorithm:

Between the Osc. In input, and the TO LOAD output, there basically lies only a voltage-to-current converter, capable of bipolar output in the range ±220 mA, with frequency response from frequency zero to above 5 kHz. The voltage-to-current progression is d.c.-coupled throughout, and ideally executes the mapping $i_{\mathrm{out}}(t) = V_{\mathrm{in}}(t)/10.\ \Omega$. The output-voltage compliance is limited to the ±10 V range, which imposes some limits on the acceptable resistance, and inductive reactance, of the load.

Overdrive at the Osc. In input will result in ‘clipping’ of the output, as the current waveform $i(t)$ will saturate at about the ±220 mA levels.

Because the current returning from the load is sensed by passing through a 1.0-Ω resistor to ground (and is thereby servoed to match V_{in}/10. V), the load must be 'floating', ie. neither of its terminals may be held at ground potential. A buffered copy of the voltage drop across this 1.0-Ω resistor, namely a ground-referenced voltage given by $i(t) \times 1.0\ \Omega$, is available to the user at the Curr. Mon. output.

Because of the bipolar and d.c.-coupled operation of the whole train from Osc. In to the load and to Curr. Mon outputs, it is possible to drive the load with non-sinusoidal currents. For example, a triangular-wave input waveform will yield a (nearly) triangular-wave current in the load, and a triangular-wave voltage waveform at the Curr. Mon. output. The waveform will suffer some distortion, in proportion to the presence of Fourier components above 5 kHz in the input waveform.

The Curr. Mon. voltage waveform is in turn the source of the Balance Output on the back panel. That output is designed for use with sinusoidal input at Osc. In, and it is always a voltage waveform having the same frequency as the drive waveform. Furthermore, it scales linearly with the size of the Osc. In waveform.

> The novelty of the auxiliary balance output is that it is fully adjustable in magnitude and phase, in the following sense: If the Curr. Mon. waveform is written as
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> $$V_{mon}(t) = V_0 \cos(2\pi\, f\, t) \quad ,$$
>
> then a modified version of this waveform, fully adjustable in magnitude and in phase, can be written as
>
> $$V_{mod}(t) = M \cdot V_0 \cos(2\pi\, f\, t - \varphi) \quad ,$$
>
> where M is a relative-magnitude factor, and φ is a phase shift. We choose to expand that phase-shifted cosine to give
>
> $$V_{mod}(t) = (M \cos\varphi)\, V_0 \cos\ (2\pi\, f\, t) + (M \sin\varphi)\, V_0 \sin\ (2\pi\, f\, t) \quad ,$$
>
> so we see that our desired output could be written as
>
> $$V_{mod}(t) = A_I \cos\ (2\pi\, f\, t) + A_Q \sin\ (2\pi\, f\, t) \quad ,$$
>
> where A_{I} and A_{Q} are the amplitudes of respectively the in-phase, and the quadrature-phase, components of the output. Note that A_{I} and A_{Q} scale linearly with V_0, and note that either might be set to have positive, zero, or negative value. The choices of A_{I} and A_{Q} jointly reflect the choice of the magnitude-factor M and the phase-shift φ chosen above, but the choice of A_{I} and A_{Q} is a simpler method for synthesizing a frequency-f waveform of arbitrary magnitude and phase.

Connections:

This SIM derives all its power from the SIM crate (or substitute power supply) into which it is plugged. It does require some external a.c. waveform generator, applied to the Osc. In connection, to provide the input waveform which controls all its outputs.

Power:

This SIM delivers at most about 0.2 A current at a potential difference of 10 V or less, so its (instantaneous) power output is limited to about 2 Watts, and its average power output to about 1 W. The SRS SIM crate makes available a total of 70 W to power all its SIMs, so there ought always to be enough power to operate the load of the Coil-Drive SIM.

Settings:

If you're a first-time user of this SIM, you might first drive it with a 1-kHz sine wave of 1 V amplitude, and you might first use a DMM, set and wired to serve as an a.c. ammeter, as its (back-panel) load. Recall that the Osc. In input and the Curr. Mon. output are both ground-referenced voltages, and you can monitor either, or both, with an oscilloscope. (By contrast, it will *not* do to attach a line-powered 'scope across the TO LOAD connections, as that would ground one side of the load.)

Recall also that for familiarizing yourself with the voltage-to-current functions of the SIM, there are no adjustments necessary (or possible). In particular, the voltage-to-current transformation will occur *whether or not* you have set the rotary switch to the correct 'band' for the frequency you've chosen.

Activation:

The whole SIM is activated as you've as you've energized the SIM crate or equivalent that is powering it. For best results, you should connect some load to the TO LOAD output connections *before* you energize the SIM, so that you will have provided a path for the flow of the current you are commanding via the input at Osc. In.

Auxiliary balance output:

Recall that this output is derived from the voltage waveform you can view at the Curr. Mon. output, so you will need first connect a load to the SIM, and next to drive the SIM with a waveform at Osc. In input, to get any response at this output. Just to be concrete, we will imagine that you have applied a 1 kHz sinusoid of 1.0-V amplitude to the Osc. In input, and have connected some compatible load at the rear-panel TO LOAD outputs. Under these circumstances, you should expect that the current through the load will be sinusoidal, of 1 kHz frequency, and of amplitude 0.1 A. Furthermore, the Curr. Mon. output should be a ground-referenced voltage sinusoid, of 1-kHz frequency, and of 0.1 V = 100-mV amplitude.

Now to get the simplest behavior out of the SIM, you should choose the 0.5-1.4 kHz 'band' setting at the SIM's rotary switch, since your chosen drive frequency falls into this band. The SIM processes that 100-mV amplitude 1-kHz Curr. Mon. waveform internally in several stages:

> First, there’s an RC-filter, which (at mid-band) attenuates the sinusoidal waveform to about 70-mV amplitude, and phase shifts it by 45°.
>
> A buffered copy of that waveform is next applied to another RC-combination, and the voltage drops across the resistor, and across the capacitor, are separately isolated. Under our assumptions, both will be of about 50-mV amplitude, and they will suffer further phase shifts of about 45° (for the one), and of 90° more than about 45° (for the other), respectively.
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> So now we have separate 1-kHz waveforms, of approximately equal amplitude, and exactly 90° out of phase with respect to each other. One of these has been contrived to be phase-shifted by approximately 90° relative to the current waveform, and the other has been phase-shifted by exactly 90° more than that, so the two separate waveforms are in (relative) ‘phase quadrature’. Now each of these waveforms is scaled by a factor, chosen in the range -1 to +1 via a front-panel 1-turn control. This is the point where the user chooses the amplitude of the in-phase, and the quadrature-phase, components.
>
> Those two waveforms are scaled down by a fixed factor of 5, and then summed to give the chosen I+Q superposition; and this result is scaled down by a factor of 1, 100, or 10, as chosen by front-panel switch. A buffered copy of the result is available as a ground-referenced output voltage at the rear of the SIM. Operating at any band center, with Osc. In set to 1-V amplitude, and using the ÷1 setting the toggle switch, the amplitudes of in-phase and quadrature-phase contents can both be set in the ±10 mV range.

When operating at a frequency not at the geometric center of a frequency ‘band’, the range-of-amplitudes of the I and Q components will no longer be exactly equal, and the I-component will no longer be exactly in phase with the Curr. Mon. waveform. But at any frequency, the components controlled by the In-Phase and Quadrature knobs will always be exactly 90° apart in their *relative* phase. The waveform ‘space’ spanned by the joint action of the In-Phase and Quadrature knobs still includes access to any phase, and (within limits) any magnitude, relative to the Curr. Mon. waveform.

Application:

The adjustable (though small) Balance Out waveform has been made available to users of the Magnetic-Susceptibility experiment as a ‘nulling waveform’. In that, or in similar experiments, excitation of the physical system (such as the Hartshorn coil) by the current-output waveform of the SIM will produce a physical output waveform, of the same frequency as the exciting waveform. (The Hartshorn secondary-coil waveform is an example of this output.) In the ideal case, the size of that output would be *zero* in the absence of a sample. In the real world, there could easily be some small but non-zero output, even in the absence of any sample. The purpose of the Balance Out of the Coil-Drive SIM is to provide access to a wholly-electronic replica of this sample-absent waveform.

Then in a typical data-taking environment, one would process the physical system’s output with electronics having a ‘differential input’ structure. To the (+) input, one would apply the physical system’s output; to the (-) input, one would apply the Balance Out signal generated by the SIM.

Then the electronics would take the *difference* of these two waveforms, and that difference would be arranged (via adjustments to the I and Q controls of the SIM) to give an algebraic cancellation of signals for the case of a sample-absent configuration. With that ‘balance’ once adjusted, any subsequent signal that is seen would be due *only* to the presence of the sample, and would be free of the ‘offset’ or imbalance otherwise appearing even in the absence of any sample.