Detecting the Ratio of I_{AC}/I_{AVE}

HINDS INSTRUMENTS

TECHNICAL NOTE

Measurement of the Average Intensity of a Modulated Light Beam

In any experiment using photoelastic modulators (PEMs) it is necessary to compare the time average intensity of the light at the detector with the amplitude of a single frequency component of the light intensity.[1,2] For example, in experiments to measure circular dichroism the effect being measured is proportional to the ratio I_f/I_{ave} where I_f is the amplitude of the Fourier series component of the light intensity function at the modulator frequency f and I_{ave} is the average of the light intensity function, integrated over a time interval much longer than the period of oscillation of the PEM.[3] The case for linear dichroism is the same, except that the frequency component needed is twice the modulator frequency, or 2f.

In many other experiments these ratios may be used to normalize the optical signal so that the results obtained are independent of fluctuations in the intensity of the transmitted light beam, for example changes in the intensity of the light source or changes in absorption, scattering, etc. in the optical components.

The measurement of this average light intensity is not trivial, and it presents some important challenges for the experimenter. Of course, what is measured directly is the electrical output of a transducer which converts the light intensity information into an electrical signal, either a current or a voltage. The problem reduces to determining the ratio of electrical signals, rather than optical quantities. The determination of these ratios. and especially the measurement of the average intensity, current or voltage is the subject of this application note.

DETECTION OF THE AC SIGNAL COMPONENT

The analysis done on the light intensity function entering the detector (or its electrical signal counterpart) is commonly based on a Fourier series analysis of this intensity function. Lock-in amplifiers are used to measure amplitudes of the AC components of this signal, for example at the modulator frequency (f), or twice the modulator frequency (2f).

The lock-in amplifier requires an input reference signal (provided by the PEM controller) which is precisely synchronized with the optical signal. The result is an electronic voltmeter with a very narrow frequency bandwidth. Typical lock-in amplifiers may be adjusted to detect f, 2f, or in some cases even higher harmonics of the PEM frequency.

The basic phase sensitive detection scheme of the lock-in amplifier is sensitive to odd harmonics of the detected signal frequency. Many typical PEM setups produce rather strong harmonic components, especially the third harmonic of the detected signal frequency. Using electronic filtering (typically provided by the lock-in) to minimize the effects of these higher harmonics is recommended.

Lock-in amplifiers provide several output modes: 1) visual, by a meter or digital display, 2) analog, a voltage output proportional to the amplitude of the detected signal, and 3) a digital output to an RS-232 or GPIB computer interface. Many lock-ins can also digitize other signals (such as the average signal component) or even compute the ratio of the lock-in output to another signal. For modern PEM setups the digital output to a computer is the probably the most important.

DETECTION OF THE AVERAGE INTENSITY COMPONENT

The average or zero frequency Fourier component of the light intensity function (or the detector electrical signal) may be determined by either of two methods: DC electronic techniques or AC electronic techniques which involve “chopping” or periodically interrupting the light beam. Each technique has its own advantages and disadvantages, with the choice frequently being dictated by the type of detector that is selected. These techniques are described in succession below.

Detection of Average Signal Components using DC Techniques

Electronic circuits with electrical bandwidths down to DC may be used for measurement of the average component of the electronic signal. Such circuits, if they can be used, have an advantage of simplicity and low cost. They have the disadvantage that electrical offsets (DC components in the electrical signal not related to the average light-intensity) must be dealt with very carefully.

Offsets

These electrical offsets arise from three main sources:

1. The dark current or intrinsic electrical signal from the detector under conditions of no light exposure.
2. Ambient light, not a part of the experiment light beam, failing on the detector.
3. Electrical offsets which arise from the electronic circuitry associated with the detector.

These electrical offsets must either be eliminated or reduced to acceptably low levels, or characterized and corrected for in the computation of the average signal, or V_{ave}, The three sources of electrical offsets are discussed in detail below.

1. **Dark current** Most detectors have a DC dark current component in their output which is an intrinsic characteristic of the device. The dark current is dependent on temperature, and in the case of detectors such as PMTs and avalanche photodiodes, strongly depends on the operating voltage applied. In many cases, it may be possible to reduce the dark current to negligible levels by cooling the detector. Silicon photovoltaic photodiodes have low dark currents at room temperature.
2. **Ambient light** The traditional method of eliminating the effect of ambient light is to operate the experimental setup in a dark environment. Alternatively, if a monochromatic light source is being used, placing a narrow band spectral filter over the detector aperture may reduce the ambient light falling on the detector to an acceptable level. This would result in much better access to the equipment during the experiment.
3. **Electrical offsets** Active electrical components such as operational amplifiers have DC offsets associated with their operation. It is usually possible to include in their circuits a means of reducing the offset to zero. In some cases such nulling circuits might also be used to compensate for dark current or ambient light effects. Caution must be used, since the null adjustment may drift with time and with changes of the operating temperature of the electronic equipment.

If DC detection techniques are being considered, a careful analysis of the offsets and their effects must be made. Questions which should be asked include: What accuracy is required in the polarization modulation measurements being made? What is the magnitude of the polarization modulation signal produced by the effect being observed? What is the magnitude and stability of the offsets in the system? Are the offsets small enough to be ignored, or can they by corrected by using electronic methods? If not, can the offsets be characterized and corrections be made during computation of the V_{AC}/V_{ave} ratio?

DETECTING THE RATIO OF I_{AC}/I_{AVE}

AVERAGE SIGNAL DETECTION

An electrical circuit for detecting an "average" electrical signal composed of complex AC and DC components is shown in Figure 1. This is an active low-pass filter circuit using an operational amplifier. The time constant τ (characteristic response time) of the circuit is given by $\tau = 1/RC$ and the output is proportional to the average voltage or current of the input signal. Of course, other circuit elements are required for practical use of this circuit.

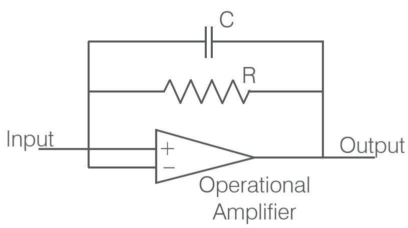

Figure 1. Operational amplifier circuit for measuring the time average of a complex periodic signal

Hinds Instruments uses this circuit in its Model SCU-100 signal conditioning unit. The instrument derives, from an input detector signal, a wide-band AC signal and a low-pass or DC signal. The signal conditioner also provides adjustable gain, primarily for the DC output. The output is an analog signal proportional to I_{ave} which is suitable for input to a digitizing circuit such as is frequently provided by a lock-in amplifier. Figure 2 shows a block diagram for typical DC-coupled signal detection.

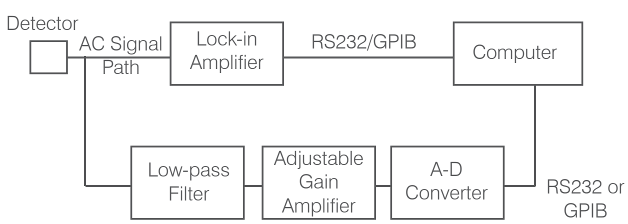

Figure 2. Block diagram for DC-coupled average signal detection

Another approach to average signal detection would be to use a digital voltmeter (DVM) connected to the output of the detector in parallel with the lock-in amplifier. Many such instruments are equipped with RS-232 or GPIB interfaces. In deciding
whether such an instrument could be used for average signal measurement, the magnitude of the expected signal, the sensitivity of the DVM, and the digital resolution of the A-D converter need to be considered. Also, the experimenter must determine that the DC measurement of a complex electrical signal is in fact proportional to the time average of the signal.

DETECTION OF AVERAGE SIGNAL COMPONENTS USING AC TECHNIQUES (CHOPPING)

The major advantage of using chopping (periodic interruption of the light beam) as a means of average signal measurement is that DC offsets are eliminated. The primary disadvantage is an additional instrument will need to added to the system.

A high-speed optical chopper is manufactured by Hinds Instruments. This chopper uses the resonance modulation of the PEM combined with a polarizer and a waveplate to produce an on/off effect at high speeds. Chopping frequencies are typically 50 kHz.

Detection of both the polarization modulated signal and the chopping signal is done using lock-in amplifiers. The most direct method is shown in Figure 3.

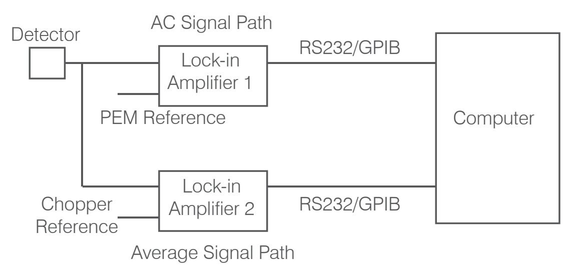

Figure 3. Block diagram for detector signal analysis using chopping for average signal detection

Lock-in amplifier I must have frequency response capable of accepting the polarization modulated signal at the modulator frequency f and twice this value, 2f. A lower frequency model lock-in (probably less expensive) may be used for lock-in 2.

Many experimental setups require the measurement of both f and 2f components of the detector signal. If this is the case, two lock-in amplifiers of type I would be required for real time measurements. If the light source and signals are stable and if measurement speed requirements are not severe, a single lock-in amplifier could be switched under computer control to measure these two quantities sequentially.

Many lock-in amplifiers have provision for calculating the ratio of the signal detected by the lock-in amplifier to another analog signal. For example, the analog output of lock-in 2 could be sent to lock-in 1, the ratio calculated and transmitted to the computer. Alternatively, the analog output of the ratio circuit could be displayed with an external digital voltmeter.

Lock-in I in Figure 3 must detect an interrupted polarization modulation signal. While the phase relationship between the polarization modulation signal and the modulator reference is preserved accurately, this situation is not ideal. Better accuracy and rejection of noise can be obtained with the setup shown in Figure 4.

For this setup, lock-in amplifier 1 must have an output

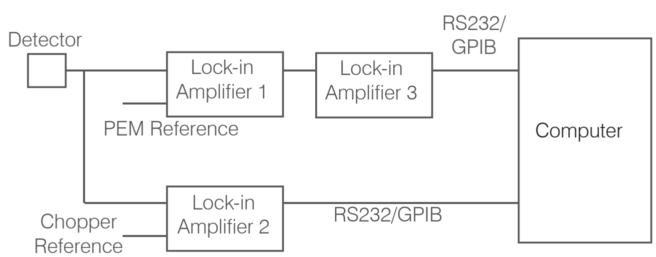

Figure 4. Alternative block diagram for detector signal analysis using chopping for average signal detection

time constant much less than the chopper period. For a chopper frequency of a few hundred kHz, a time constant of 1 msec or less would be required. Usually this dictates the use of a high quality analog lock-in amplifier.4 Lock-in amplifier 3 has frequency requirements similar to lock-in 2.

CALIBRATING THE RELATIONSHIP BETWEEN V_{AC} AND V_{AVE}

Whether AC or DC electronic techniques are used for detecting the average signal V_{ave} an arbitrary experimental constant is likely to appear in the output signal and thus in the ratio of V_{AC}/V_{ave}. In the case of a Hinds signal conditioner, it is likely that some amplification has been used in the average signal circuit. In the case of the lock-in amplifier, the use of filters or chopping may alter the response of the instrument. The lock-in amplifier also measures r.m.s. quantities, whereas polarization modulation theory gives peak or amplitude quantities.

There is therefore a need to produce an optical signal for which the ratio of I_{AC}/I_{ave} is known with precision. Use of such a signal will enable the experimenter to determine the experimental constant K_1 which relates the ratio of the experimental outputs to the ratio of optical intensities, as given in equation 1.

$$\frac{I_{AC}}{I_{ave}} = K_1 \frac{V_{AC}}{V_{ave}} \quad (1)$$

Fortunately this is easily done with the PEM and other equipment common to polarization modulation experiments. Figure 5 shows the optical setup for determining the experimental constant K_1.

In general, this experimental setup should resemble as closely as possible the optical bench setup for the experiment in question. Some additional precautions need to be mentioned. First, if the light source is a laser, the effects of modulated interference must be minimized or eliminated.[5] Second, the polarizers should be of high quality (such as Glan-Thompson calcite polarizers) with very good extinction characteristics. Third, all DC

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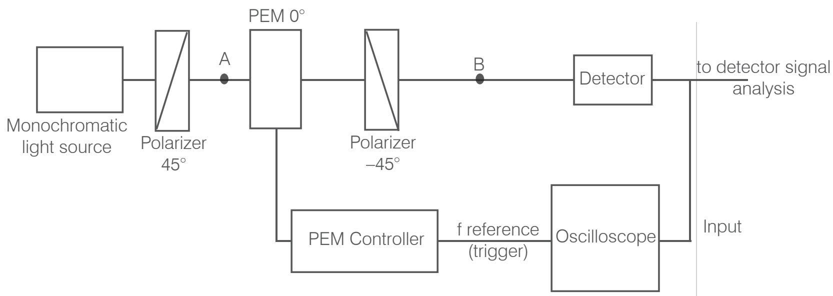

Figure 5. Optical bench set-up for V_{AC}/V_{ave} calibration

offsets must be minimized or eliminated, or properly compensated for in the calculation of V_{ave}.

Jones calculus analysis of the above optical setup leads to the following expression for the time-dependent intensity of the light at point B.[6] The intensity of the linearly polarized light at point A is I_0

$$I = \frac{I_0 K_2}{2}\left[1 - \cos(A_0 \cos(\Omega\tau))\right] \quad (2)$$

where K_2 is an experimental constant which corrects for the transmission losses in the PEM and second polarizer, A_0 is the peak retardation of the PEM expressed in units of phase angle (e.g. radians) and the angular frequency $\Omega = 2\pi f$.

Expanding equation 2 in a Fourier series yields equation 3, which displays the terms (I_{ave} and I_{2f}) involved in the intensity function. The functions $J_n(A_0)$ are Bessel functions of integer order.

$$I = \frac{I_0 K_2}{2}\left[\underbrace{1 - J_0(A_0)}_{I_{ave}} + \underbrace{2J_2(A_0)}_{I_{2f}}\cos(2\Omega t) - 2J_4(A_0)\cos(4\Omega t) + \ldots\right] \quad (3)$$

The ratio of the AC intensity amplitude (I_{2f}) to the average intensity (I_{ave}) is therefore given by:

$$\frac{I_{2f}}{I_{ave}} = \frac{2J_2(A_0)}{1 - J_0(A_0)} \quad (4)$$

The condition of half-wave peak retardation is particularly useful for this calibration. The oscilloscope waveform is very distinctive, as shown in Figure 6.

The characteristic flat top (or flat bottom) of this waveform can be used to establish that the PEM has been accurately adjusted to half-wave retardation. (See the Calibration Application Note.) [7] For $A_0 = \pi$, $J_0(\pi) = -0.30424$ and $J_2(\pi) = 0.48543$, giving

$$\frac{I_{2f}}{I_{ave}} = 0.744 \quad (5)$$

This with the experimentally determined ratio V_{2f}/V_{ave} is sufficient for determining the constant K, in equation 1.

References

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2. A.F. Drake, "Polarization modulation--the measurement of linear and circular dichroism," J. Phys. E. 19, 170-181 (1986).
3. Note: In many articles on this subject the notation "I_{DC}" or "V_{DC}" is used rather than I_{ave} and V_{ave}. The latter notation will be used in this application note to avoid confusion when electronic techniques are discussed later.
4. Mr. Ted Schurter, EG&G Instruments, Princeton Applied Research. Private communication
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