DISTIMULUS CHROMATIC MEASUREMENT SYSTEMS

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Abstract: - A number of different chromatic measurement systems have been developed based upon logarithmic, linear and digital signal processing. A comparison between the logarithmic and the linear system shows that the linear system is far more versatile and sensitive, capable of operation at considerably lower optical power, has a higher resolution, although it is more expensive. The performance of the digital system is comparable to the linear system but at a cost similar to that of the logarithmic system. In general, the chromatic approach provides a powerful and flexible measurement method with attractive advantages over intensity and two wavelength modulation techniques.

Key-Words: - chromatic modulation, chromatic measurement systems

1 Introduction

There are many situations in which the optical measurement of a physical parameter would be of benefit to industry. For example, optical systems can be used safely in hazardous environments and also in areas where high magnetic or electrical fields make electronic systems inadequate. However, the uptake by industry of optical technology has been slow either because of a lack of confidence in the technology or because optical monitoring tends to be specialized, expensive and insufficiently robust to withstand the industrial environment.

Of the methods available for modulating light (e.g. amplitude, phase, polarization changes) intensity modulation offers the advantages of inherent simplicity. However, conventional methods involving absolute intensity have associated problems. The most basic intensity monitoring systems use only a single photodiode to produce an output but these systems tend to be sensitive to spurious changes in intensity resulting from variations in the light source or other components within the system. Removing these spurious effects is difficult and leads to complicated and expensive systems. Wavelength monitors attempt to deduce the state of a system by taking the ratio of intensities at two different wavelengths. In principle, the two wavelengths should be chosen to be close enough together to ensure that spurious signals affect both wavelengths equally. However, the modulator needs to affect only one of the wavelengths so leading to conflicting demands. Such wavelength modulated systems may be constructed using spectrometers or by using two narrowband optical filters in conjunction with two photodetectors. Systems which make use of a spectrometer are expensive, optically inefficient and, require excessive data processing. Systems using filters and photodetectors are less expensive, but are wasteful of optical power. Such systems may also be used for wavelength encoding detection but the spectrometer approach leads to improved resolution only at the expense of optical power whilst the narrow-band filtered photodiodes only have a limited range of operation.

Many of the difficulties inherent in the spectral or two wavelength monitoring methods may be overcome using a chromatic measurement system. A number of sensors based upon this approach have been developed [1, 2] and shown to possess attractive advantages. Such systems measure changes in the spectral signatures of polychromatic light using carefully configured combinations of broad band detectors. The technology evolves from the study of colour vision [3]. The chromatic approach provides a powerful and flexible measurement method whose full potential is still being explored. This contribution seeks to describe some of the fundamental aspects of chromatic measurement systems which are relevant for optical sensing applications. These are based upon the understanding that although the considerations derive from the concepts of colour science [4, 5, 6, 7], e.g. chromaticity diagrams, dominant wavelength etc, they need to be adapted in fundamentally different ways for their advantages to be fully exploited.

2 Chromatic Modulation Theory

The essence of chromatic modulation is the utilisation of polychromatic light for sensing spectral changes by monitoring the total profile of an optical signal within a spectral power distribution. Chromatic changes can be monitored by a number (*n*) of detectors with overlapping spectral responses. The output of each detector may then be expressed as [8]

$$V_n = \int P(\lambda)R_n(\lambda)d\lambda \qquad (1)$$

where P(λ) is the spectral power distribution in the optical signal and $R_n(\lambda)$ is the wavelength responsivity of the nth detector and λ is the wavelength. The chromatic model representing this mathematical formalism is generally called RGB and it is widely used in self-luminous display technologies. Each detector output may also be intensity normalised according to:

$$u_n = \frac{V_n}{\sum_n V_T} \qquad (2)$$

where

$$u_1 + u_2 + \ldots + u_{(n-1)} + u_n = 1 \qquad (3)$$

In such a way, chromaticity maps may be formed in terms of the coordinates u_1, u_2, … $u_{(n-1)}$. The case of n=2 leads to a distimulus chromaticity map on which either chromaticity coordinate (u_1 or u_2) may be used to completely describe changes in optical signals. Any two detectors with different but overlapping spectral responses may be used to form a distimulus measurement system.

2.1 Distimulus detection

The two-dimensional nature of the chromaticity diagram, shown in Fig. 1, implies that in general, the status of the measurand is over-specified in being defined by two coordinates, u_1, u_2.

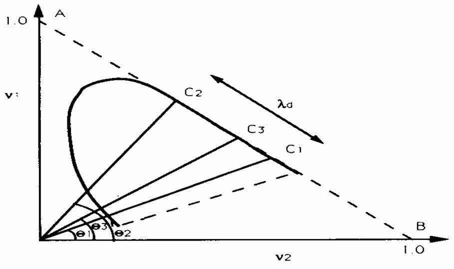

Fig. 1. Chromaticity diagram for distimulus detection.

System simplification and implementation economy is therefore possible by reducing the amount of information acquired and which may be achieved through the use of two rather than three detectors (this differs from two wavelength monitoring in being broad-band and often using overlapping detectors). The measured status is then defined by the single variable.

$$\tan\theta = \upsilon_1 / \upsilon_2 \qquad (4)$$

which in chromaticity terms is effectively a measurement of the shift in dominant wavelength. The two detector (distimulus) system can, therefore, be used to measure those spectral signature changes which lead to a change in dominant wavelength. Since the ratio υ_1 / υ_2 provide normalization with respect to signal intensity the distimulus method preserves the intensity-independent nature of chromatic monitoring. Also, since the signals υ_1 and u_2 are derived from overlapping detector responses, there is a degree of inbuilt immunity to extraneous spectral noise in the output υ_1 / υ_2.

2.2 Performance criteria

The performance criteria of a chromatic measurement system include the range, sensitivity and resolution. With chromatic sensing these criteria need to be defined with respect to fundamental chromaticity concepts to enable comparisons to be made between various sensor types. With the distimulus system the range is determined by the change in dominant wavelength which for conventional optical fibre systems is governed by the fibre transmission window. This is typically 500 nm to 1 µm so yielding a dynamic range of 500 nm. The minimum detectable chromatic signal change which is governed by electronic processing noise has been measured to be typically 0.01 nm. This implies a resolution of 5 x 10^4.

3 Distimulus Measurement Systems

Distimulus measurement systems provide a relatively simple, intensity independent method of classifying different complex spectral signatures in terms of the dominant wavelength. In many applications this chromatic parameter of a spectral signature is adequate to uniquely describe the state of the measurand. Three different types of distimulus systems have been developed based upon logarithmic, linear and digital signal processing.

3.1 Logarithmic measurement of dominant wavelength

A schematic diagram of a logarithmic dominant wavelength measurement system is given in Fig. 2.

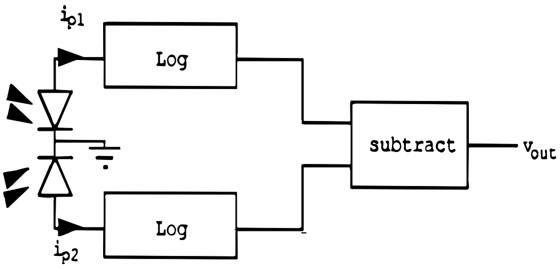

Fig. 2. Schematic diagram of the logarithmic distimulus measurement system

The photocurrents i_{pl} and i_{p2} are amplified logarithmically, to provide two voltages proportional to log i_{pl} and log i_{p2}. The difference between these two voltages is calculated which yields an output voltage proportional to log (tan θ), as shown in Eq. 5.

$$\log i_{pl} - \log i_{p2} = \log i_{pl} / i_{p2} = \log (\tan \theta) \qquad (5)$$

Minimum operational light intensity	6.7mW m-2
Resolution	0.11 nm
Error in dominant wavelength for 1% change in intensity	0.031 nm/%

Table 1. Summary of the logarithmic distimulus measurement system specification

3.2 Linear distimulus measurement system

Fig. 3 shows a schematic diagram of a distimulus measurement system whose output is a linear function of tan θ. The photocurrents i_{pl} and i_{p2} are converted into voltages using transresistance amplifiers. These voltages are divided by an analogue divider to produce an output voltage, Vout, proportional to tan θ.

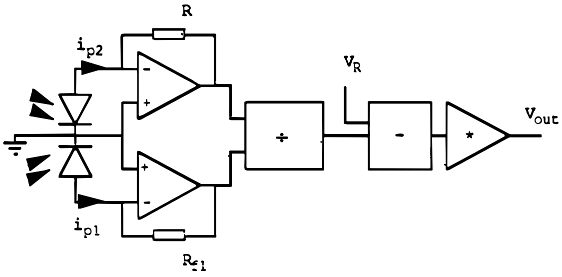

Fig. 3. Schematic diagram of the linear distimulus measurement system

In order to measure small changes in tanθ, a post division processing stage is incorporated. This stage allows a reference voltage, V_R, to be subtracted from the divider output to zero Vout with the measurand at some initial value. The final stage is a variable gain stage which allows the maximum value of Vout to be set to correspond to the final value of the measurand. These adjustments condition the system to maximum average sensitivity over the full range of the measurand. The overall transfer function of the linear distimulus measurement system is described by Eq. 6.

$$V_{out} = G\left[\frac{i_{p1}R_{f1}}{i_{p2}R_{f2}} - V_R\right] \qquad (6)$$

Where Vout is the output voltage which is analogous to tanθ, G is the gain factor, i_{pl} and i_{p2} are the photocurrents, R_{fl} and R_{f2} are the trans-resistance amplifier feedback resistor values, and V_R is the offset voltage.

Minimum operational light intensity	1µw m-2
Resolution	~ 0.0095 nm
Error in dominant wavelength for 1% change in intensity	0.00031%

Table 2. Summary of the linear distimulus measurement system specification

3.3 A digital distimulus measurement system

The most expensive parts of the linear distimulus measurement system are the operational amplifiers used in the transresistance amplifiers and the analogue divider. The cost of the linear system prompted consideration of the use of a low cost analogue to digital converter (ADC) to perform the division required to obtain the value of tan θ in a digital format.

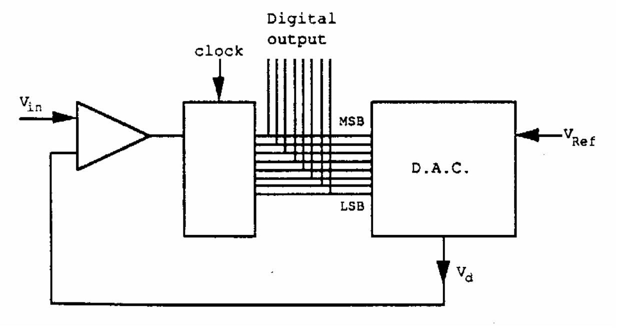

Fig. 4. Schematic diagram of the ADC operation

Two ADC's were used, the Ferranti ZN 448 and the ZN 502, which work on the successive approximation technique. A successive approximation ADC has three main components, a comparator, a digital to analogue converter (DAC) and a control counter and latch, as shown in Fig. 4. Vin is the analogue input voltage to be converted into a digital representation, Vref is an analogue reference voltage and Vd is the DAC output voltage. The operation of the ADC calculates the digital input value to the DAC required for the output voltage, Vd, to equal the input voltage Vin.

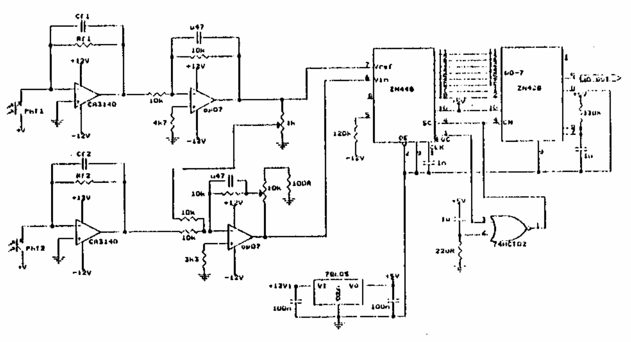

Fig. 5. Schematic diagram of the ADC operation

Fig. 5 shows a schematic diagram of the digital distimulus system. The performance of this system is comparable to the linear system although at a cost similar to that of the simple logarithmic system.

Minimum operational light intensity	46.6 mW m-2
Resolution	~ 0.02 nm
Error in dominant wavelength for 1% change in intensity	0.0004%

Table 3. Summary of the digital distimulus measurement system specification

4 Conclusion

The specifications of the linear and logarithmic distimulus measurement systems show the linear system to be far more versatile and sensitive. The linear system is capable of operation at considerably lower optical powers (1 μW m^{-2} compared with 6.7 m W m^{-2} for the logarithmic systems), has a higher resolution (0.0095 compared with 0.11 nm) and a smaller error in chromaticity for a change in intensity (<0.00013 nm/% compared with 0.031 nm/%). However, the cost of the linear system is an order of magnitude greater than that of the logarithmic system. The most expensive items in the linear system are the two operational amplifiers in the trans-resistance stage and the analogue divider. The performance of the digital system is comparable to the linear system although at a cost similar to that of the simple logarithmic system. The potential and versatility of the approach derives from the possibility of controlling the system range and resolution by suitable choice of the photodetectors employed, from the intensity independent nature of the method, and from the high optical efficiency of the technique.

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