CHAPTER 2

FUNDAMENTAL CHARACTERISTICS

The fundamental characteristics of any given type of photomultiplier are specified in its data sheets. This chapter describes what they are, what they signify, how some of them are measured and, finally, how they are commonly presented in the data sheets. Some of the characteristics relate to the tube as a whole, others to only one of the three functional parts

– photocathode
– electron-optical input system
– electron multiplier and anode.

Collectively, they can be divided into four classes relating to sensitivity, time, dark current, and energy resolution. (Stability and linearity characteristics are dealt with separately in Chapter 4.)

2.1 Sensitivity characteristics

2.1.1 Photocathode sensitivity S_k

This is the ratio of the cathode current I_k (less the dark current, see §2.3) to the incident flux Φ. Expressed in radiometric units it is called *cathode radiant sensitivity*:

$$S_k(\mathrm{A/W}) = \frac{I_k\ (\mathrm{A})}{\Phi_e\ (\mathrm{W})} \tag{2.1}$$

Expressed in photometric units it is called *cathode luminous sensitivity*:

$$S_k(\mathrm{A/lm}) = \frac{I_k(\mathrm{A})}{\Phi_v(\mathrm{lm})} \tag{2.2}$$

In most applications the radiation is not monochromatic but has a spectral composition to which the cathode is not uniformly sensitive (see Fig.1.3 and 1.4). To specify the photocathode sensitivity completely, therefore, it is also necessary to specify the spectral composition at which the stated sensitivity was measured.

Cathode radiant sensitivity

The radiant sensitivity is customarily specified for a specific wavelength λ. If $d\Phi_e$ is the incident flux increment in a wavelength increment $d\lambda$ centred on λ, and dI_k is the corresponding cathode current increment, then

$$S_{k,\lambda} = \lim_{d\lambda \to 0} \frac{dI_k}{d\Phi_e}$$

is the *monochromatic sensitivity* or *absolute spectral sensitivity* at the wavelength λ.

Relative spectral sensitivity is the ratio between the sensitivity at a given wavelength λ and at a reference wavelength, usually the one at which sensitivity is greatest. It can differ appreciably from one tube to another of the same type, particularly in the neighbourhood of the photoemission threshold and especially in tubes with S20, S20R or S1 cathodes. The radiant sensitivity of S20 cathodes, for instance, may vary by a factor of 10 at 800 nm but by a factor of only 2 at 450 nm.

Cathode luminous sensitivity

The luminous sensitivity is usually specified for a spectral composition that is typical for a particular application. A customary distinction is:

- luminous sensitivity to white light, which is used to characterize tubes intended for photometry; the reference illuminant for specifying this is a tungsten-filament lamp with a colour temperature of 2856 K.
- luminous sensitivity to blue light, which is used to characterize tubes intended for scintillation counting. (The emission of many scintillators peaks at about 430 nm.) This sensitivity, also called CB (Corning Blue) sensitivity, is based on the light of a 2856 K tungsten-filament lamp transmitted through a Corning C.S. No. 5-58 filter ground and polished to half stock thickness (Fig.2.1). In the data sheets this is specified as 'blue sensitivity' expressed in µA/lmF (where F stands for filtered, indicating that the same unit can be used also for other specified filters, e.g for 'red sensitivity').

For a bialkali cathode (see Fig.1.3) the ratio of CB to white-light luminous sensitivity is

$$\frac{S_k\ (\mathrm{C.B.})}{S_k\ (\mathrm{white})} \approx 0.15$$

Radiant sensitivity is often specified at 400 nm; the relation between CB luminous sensitivity and the radiant sensitivity at 400 nm is

$$\frac{S_k\ (\mathrm{CB})}{S_{k,400\,\mathrm{nm}}} \approx 0.125 \times 10^{-3}\ (\mathrm{W/lm})$$

Both these relations are subject to some variation from tube to tube.

Cathode sensitivity is never uniform over the whole surface of the cathode; moreover, the non-uniformity varies with wavelength (see Fig.4.3). For some applications it may be important to measure this non-uniformity and its wavelength dependence.

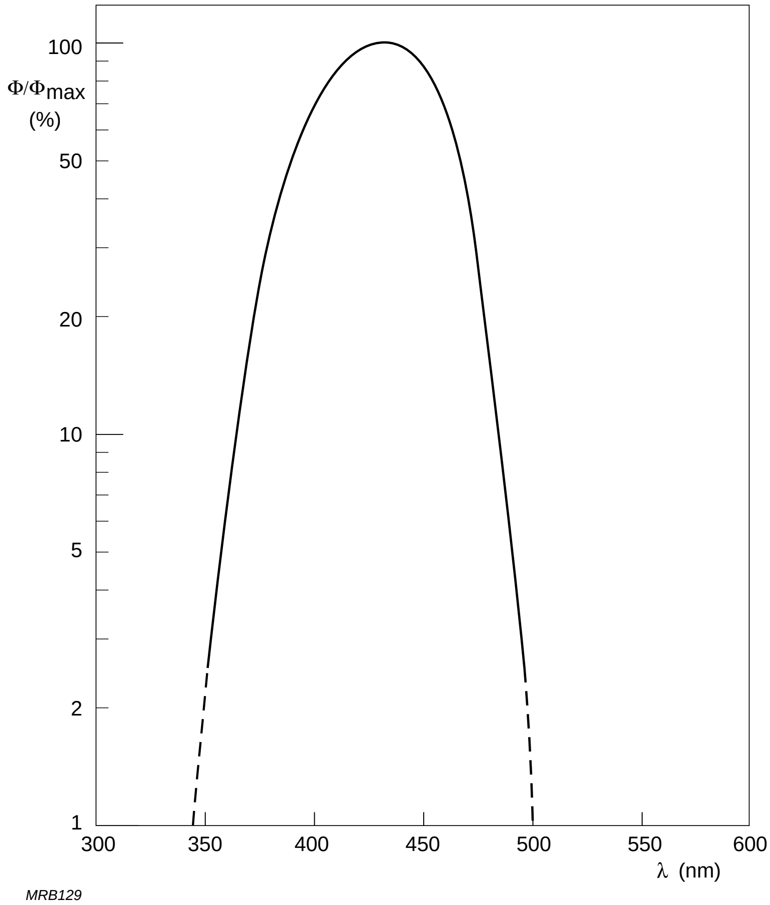


Fig.2.1 Relative spectral sensitivity characteristic of 2856 K tungsten light transmitted by a Corning filter CS No. 5-58 ground to half stock thickness

2.1.2 Quantum efficiency, ρ

This characteristic, which is another way of expressing cathode sensitivity, is the ratio of the number of photoelectrons emitted, n_k, to the number of incident photons, n_p. It is usually specified for *monochromatic* light and is related to the absolute spectral sensitivity by

$$\rho = \frac{n_k}{n_p} = S_{k,\lambda} \frac{h\nu}{e} = S_{k,\lambda} \frac{hc}{\lambda e}$$

where e is electron charge, h is Planck's constant, and c is the speed of light in vacuum. With $hc/e = 1.24 \times 10^{-6}$ Wm/A

$$\rho(\%) = 124 \frac{S_{k,\lambda}(\mathrm{mA/W})}{\lambda \ (\mathrm{nm})} \tag{2.3}$$

The curves of uniform quantum efficiencies drawn in Fig.1.3 illustrate the extent to which the quantum efficiencies of standard cathodes vary with wavelength.

For light that is not monochromatic, the ratio of the number of photoelectrons emitted to the total number of incident photons (in the region where the incident light spectrum and the cathode sensitivity spectrum overlap) is called the *integral quantum efficiency*. This is often an important specification in high-energy physics applications involving scintillators and wavelength shifters (§7.4).

2.1.3 Input system collection efficiency, η

This is the ratio between the number of photoelectrons reaching the first dynode and the number leaving the cathode, usually expressed in per cent. It is a function of the initial velocities of the electrons and therefore varies with wavelength, decreasing at shorter wavelengths as the photon energy increases (Fig.2.2); a slight recovery is observable at wavelengths below about 200 nm for which so far no satisfactory explanation has been put forward. Like cathode sensitivity, collection efficiency is not uniform with respect to the whole cathode surface; it also varies according to the geometry of the input system. The non-uniformity is a function of wavelength and is a measurable quantity. No universally accepted methods exist for measuring absolute collection efficiency, and it is often more useful to speak about *relative collection efficiency*, i.e. efficiency relative to a well-defined situation, for example an energy-resolution measurement.

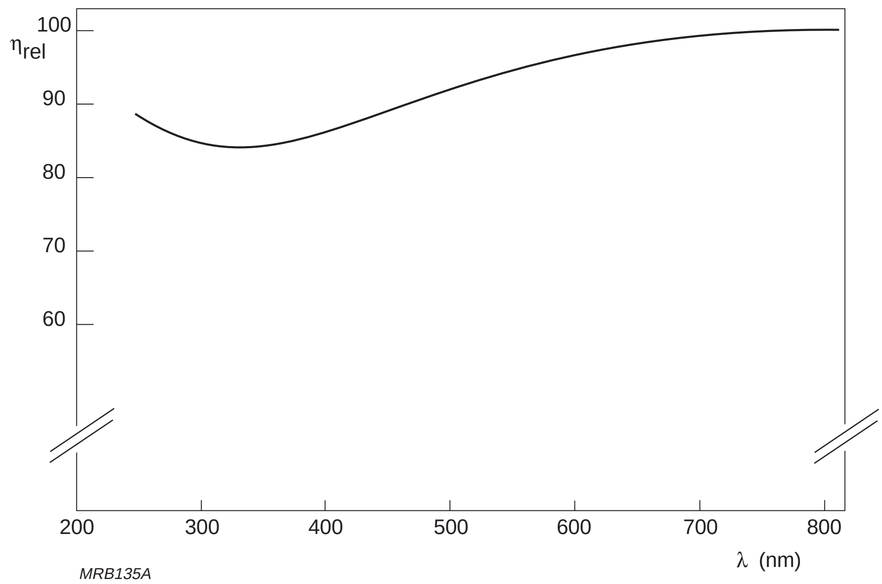


Fig.2.2 Example of relative input system collection efficiency as a function of wavelength

Collection efficiency depends on the voltage applied between the cathode and first dynode. Under optimum conditions it is possible to obtain a mean collection efficiency of more than 80%, averaged over the whole cathode surface, for wavelengths longer than 400 nm.

2.1.4 *Gain, G*

The gain of a photomultiplier is the ratio I_a/I_k, where I_a is the anode current due to a cathode photocurrent I_k:

$$G = \frac{I_a}{I_k} \tag{2.4}$$

For an N-stage tube in which η is the collection efficiency of the first dynode, δ_i the secondary emission coefficient of the *ith* dynode, and η_i the collection efficiency of the *ith* multiplier stage,

$$G = \eta(\delta_1\eta_1)(\delta_2\eta_2)\ ...\ (\delta_N\eta_N) = \eta\prod_{i=1}^{N}\delta_i\eta_i = \eta\prod_{i=1}^{N}g_i \tag{2.5}$$

where g_i is the gain of the *ith* stage.

The gain increases rapidly as a function of the applied voltage. If the collection efficiency of all stages approaches 100%, from Eqs 1.3 and 2.5

$$G = \prod_{i=1}^{N}k_iV_i^{\alpha} \tag{2.6}$$

where k_i is a proportionality constant, V_i the interdynode voltage per stage, and α is between 0.6 and 0.8. As V_i is a fraction k'_i of the supply voltage V_{ht}, this can be written

$$G = \prod_{i=1}^{N}k_i(k'_i)^{\alpha}V_{ht}^{\alpha} = KV_{ht}^{N\alpha} \tag{2.7}$$

where the constant K depends on the material of the dynodes and the voltage division between them. Thus, for a 10-stage tube the gain increases as about the 7th power of the supply voltage (see Fig.2.7), doubling for each 10% voltage increase. With present-day tubes, gains of 10^6 are often obtained at supply voltage between 800 V and 1200 V.

The ratio M of the gain to the input system collection efficiency η,

$$M = \frac{G}{\eta} = \prod_{i=1}^{N}g_i \tag{2.8}$$

represents the gain of the electron multiplier alone; that is, the number of electrons delivered to the anode for each electron received at the first dynode.

Gain varies somewhat with temperature, incident-light wavelength, and mean anode current.

2.1.5 *Anode sensitivity, S_a*

This is the ratio of the anode current I_a to the incident flux Φ. Like photocathode sensitivity, it can be specified in radiometric or photometric terms.

Anode radiant sensitivity

$$S_a(\mathrm{A/W}) = \frac{I_a(\mathrm{A})}{\Phi_e(\mathrm{W})} \tag{2.9a}$$

where Φ_e is the total radiant flux measured over the whole spectrum.

Anode spectral sensitivity

$$S_{a,\lambda}(\mathrm{A/W}) = \lim_{d\lambda \to 0} \frac{dI_a(\mathrm{A})}{d\Phi_e(\mathrm{W})} \tag{2.9b}$$

where $d\Phi_e$ is the flux increment in a wavelength increment $d\lambda$.

Anode luminous sensitivity (e.g. to white or blue light),

$$S_a(\mathrm{A/lm}) = \frac{I_a(\mathrm{A})}{\Phi_v(\mathrm{lm})} \tag{2.10}$$

where Φ_v is the luminous flux measured in the spectrum of interest. In the data sheets anode blue sensitivity is expressed in A/lmF (where F stands for filtered).

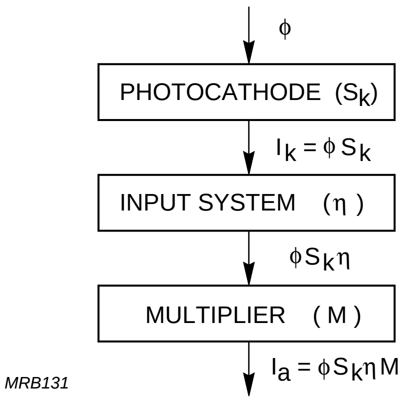


Fig.2.3 Photomultiplier sensitivity characteristics

Anode sensitivity can also be expressed in terms of cathode sensitivity, input system collection efficiency, and multiplier gain (Fig.2.3):

$$S_a = \frac{I_a}{\Phi} = S_k \eta M \tag{2.11}$$

or, from Eq.2.8,

$$S_a = GS_k \tag{2.12}$$

The sensitivity characteristic measured at the anode does not correspond exactly to that of the cathode. The differences are due mainly to the variations of η as a function of wavelength, especially in the ultraviolet.

2.1.6 Single-electron spectrum (SES)

When a photomultiplier is used to detect very weak signals such that the pulses from individual photoelectrons are well separated in time, it is often advantageous to count those pulses. Because of the nature of the secondary-emission process (§ 3.2.5), the single-electron pulses show very large amplitude fluctuations.

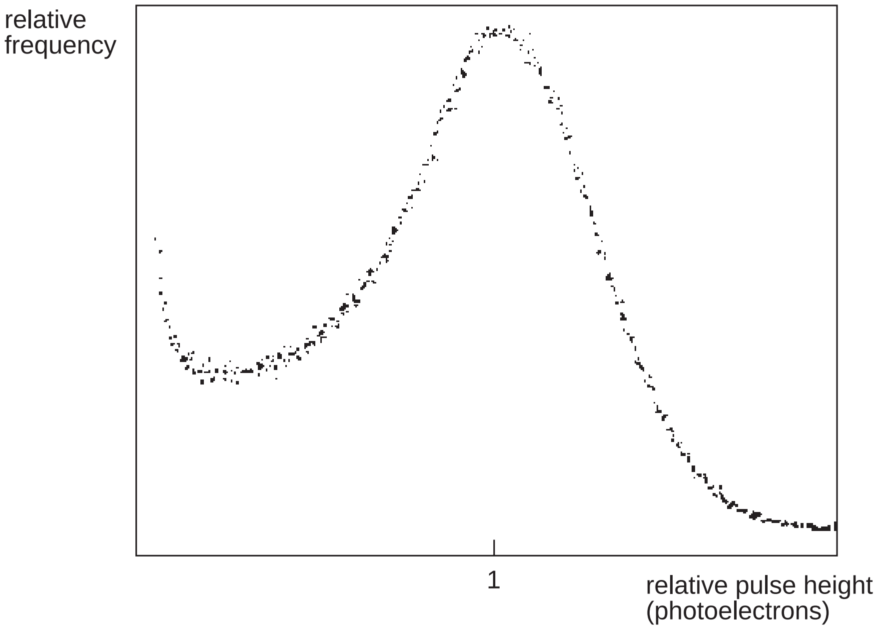


Fig.2.4 Typical single-electron spectrum. Resolution 67% FWHM. Peak-to-valley ratio 2.8:1

The corresponding amplitude distribution (or *single-electron spectrum)* can be observed with a multi-channel pulse-height analyser (Fig.2.4) and can be described by several parameters:

- the amplitude corresponding to the centroid of the spectrum. This is, of course, the *mean* amplitude; if the secondary emission were free from any fluctuation, all pulses would have that amplitude
- the peak-to-valley (P/V) ratio. With a secondary-emission coefficient for the first dynode of at least 6 to 8, the SES will show a peak and a P/V ratio can be estimated. This can be used for monitoring the actual gain of the photomultiplier. The P/V ratio is often given in the data sheets

– single-electron resolution. If the first dynode has a high secondary-emission coefficient (above 12), the P/V ratio may exceed 2 and it is possible to estimate a single-electron resolution. This is defined as the FWHM of the single-electron peak divided by the position of the peak on the multichannel analyser (expressed as a percentage). Events producing 2 simultaneous photoelectrons will give a second peak with twice the pulse height
– relative variance for the distribution.

Note: there is always a large proportion (10 to 20%) of very small pulses (below 1/3 of the single-electron peak position). They are real *signal* pulses caused by photoelectrons being inelastically back-scattered by the first dynode.

2.2 Time characteristics

2.2.1 Response pulse width, t_w

This is defined as the full width at half maximum (FWHM) of the anode current pulse delivered in response to a delta-function light pulse (Fig.2.5). Although it is not practicable to generate true delta-function light pulses, it is practicable to generate light pulses whose FWHM is much less than that to be measured. If $t_{w,l}$ is the FWHM of such a light pulse, and $t_{w,a}$ the FWHM of the corresponding anode current pulse, the response pulse width t_w is given by

$$t_w = \sqrt{t_{w,a}^2 - t_{w,l}^2} \tag{2.13}$$

provided both $t_{w,a}$ and $t_{w,l}$ are approximately gaussian. If t_w is more than a few nanoseconds, it can be satisfactorily measured using light pulses of 1 ns FWHM.

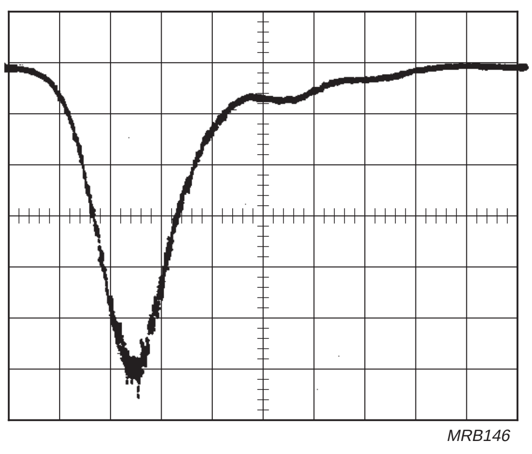


Fig.2.5 Anode current pulse response of a fast-response photomultiplier: vertical scale 20 mA/div., horizontal scale 2 ns/div

Modern lasers are capable of generating light pulses with FWHM < 100 ps. Such lasers are expensive, however, and are usually only found in advanced measuring systems. Today, new blue-emitting fast (1 - 2 ns) LEDs are commonly used.

The response pulse width depends on the illumination level and is minimum when this level is so low that the probability of more than one photoelectron being emitted per light pulse is very small (§4.4.2); this is called the single-electron response (SER). In fast photomultipliers, t_w increases by a few tenths of a nanosecond when the amplitude of the anode pulse increases from a few milliamperes (single-electron operation) to, say, a hundred milliamperes (multi-electron operation).

2.2.2 Rise time, t_r

Step-response rise time is properly defined as the time required for the anode current to increase from 10% to 90% of its final value in response to a unit step input ε(t). Measured under these conditions, the rise time $t_{r,\varepsilon}$ (Fig.2.6(b)) approximately equals the response pulse width t_w.

However, due to the difficulty of producing unit steps of light, the rise time is by convention defined as the 10% to 90% rise time of the anode current pulse in response to a light pulse that approximates a delta function (Fig.2.6(c)). This is designated $t_{r,\delta}$, or more simply t_r. It varies from about 1 ns for photomultipliers with linear-focusing dynodes to about 20 ns for those with venetian-blind dynodes or box first dynodes.

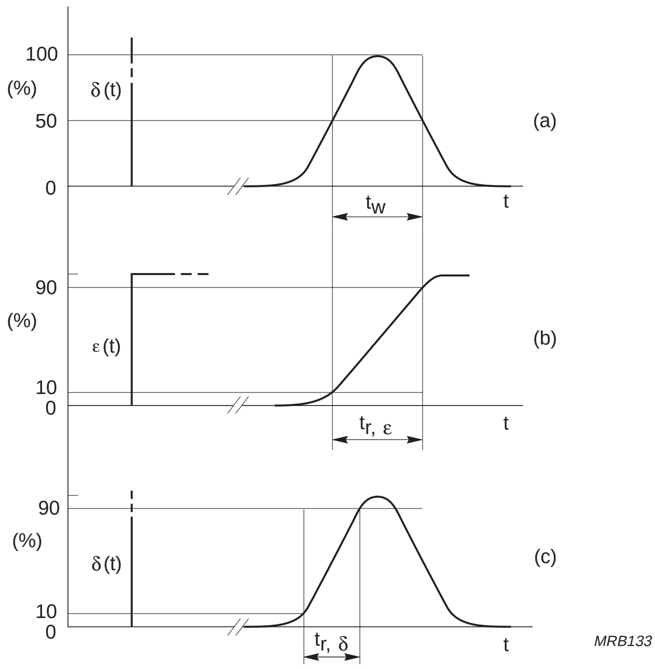


Fig.2.6 Delta-function input response-pulse width t_w, step-function input response rise time $t_{r,\varepsilon}$, and delta-function input response rise time $t_{r,\delta}$

2.2.3 *Transit-time differences*

The interval between the arrival of a light pulse at the cathode and that of the corresponding current pulse at the anode is called the transit time. Its mean value $\overline{t_t}$, evaluated over a statistically large number of pulses, varies as $1/\sqrt{V_{ht}}$ and is usually of the order of several tens of nanoseconds.

In general, the mean transit time differs according to where on its surface the cathode is illuminated. When measured with reference to one point of illumination at the centre of the cathode and another at the edge, the corresponding transit-time difference is called the *centre-edge difference* (often referred to as Δt_{CE}).

2.2.4 *Transit-time spread, time resolution*

Transit time spread ('jitter') is the transit-time fluctuation observed when identical light pulses strike the same part of the cathode (Fig.2.7). The time resolution of a tube, R_t, is defined as the FWHM of the probability distribution of the fluctuations. It is practically proportional to $1/\sqrt{n_{k,i}}$, where $n_{k,i}$ is the number of photoelectrons per pulse. Like the transit-time differences, the time resolution depends on the size and location of the illuminated part of the cathode; it also depends on the voltage applied to the electron-optical input system and on the spectral character of the illumination.

In the data sheets, transit-time spread is specified in terms of the standard deviation σ of the probability distribution of the transit-time fluctuations. It is a worst-case value (as defined by IEC) based on single-photoelectron pulses originating from points distributed over the whole surface of the cathode ('open cathode'), i.e. including the centre-edge difference.

How the time characteristics of a photomultiplier depend on the different parts of the tube, such as the input system, the multiplier, and the anode collection space, is dealt with in Chapter 4.

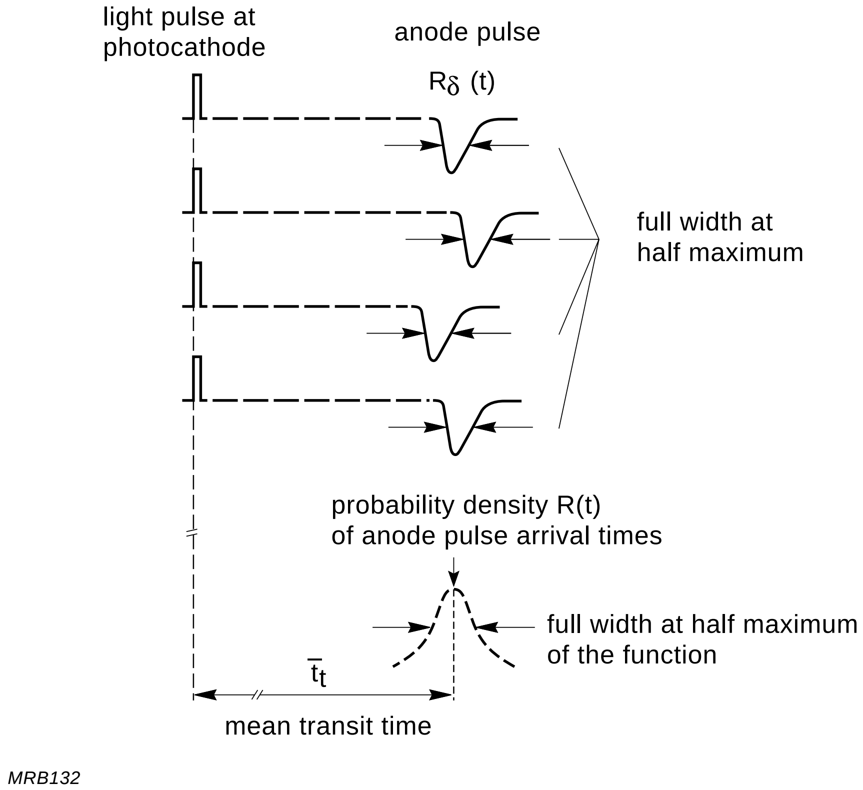


Fig.2.7 Response-pulse jitter due to transit time fluctuations

2.3 Dark current

Even in total darkness, a current can still be measured at the anode of a photomultiplier; its causes include thermionic emission, field effects, and leakage currents. It depends particularly on the composition of the cathode, and, throughout the usual range of supply voltages, varies ideally as the gain (Fig.2.8).

Observation of the dark current using a wide-band oscilloscope reveals pulses of widely varying amplitudes (Fig.2.9). These are called dark current pulses, or dark noise pulses. Integrating the dark pulses yields one component of the dark current.

The amplitude distribution, called the dark current pulse spectrum, varies according to the type of dynode (Fig.2.10), but it is often still broader than the SES, and the shape may vary considerably between different samples of the same tube.

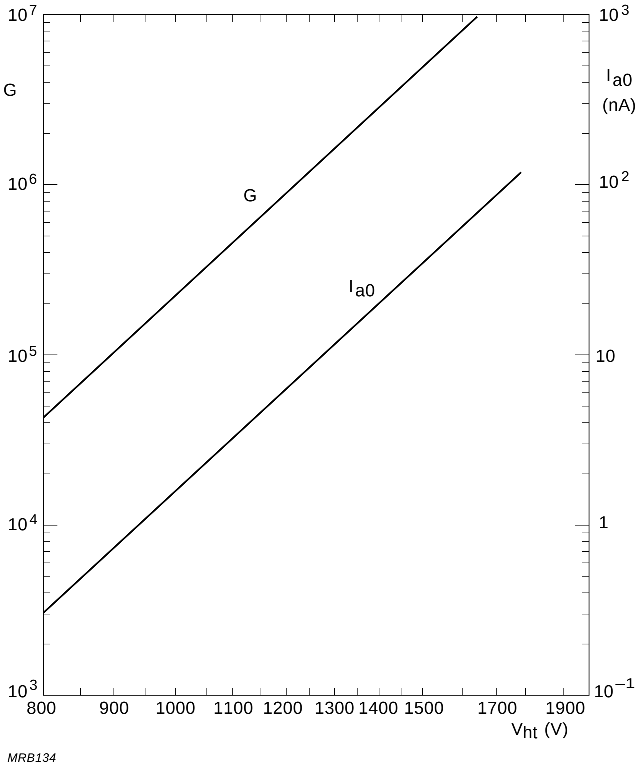


Fig.2.8 Examples of photomultiplier gain and anode dark-current variation as functions of applied voltage

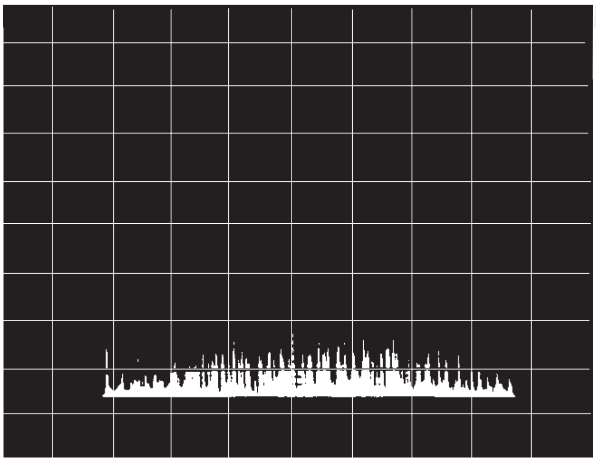
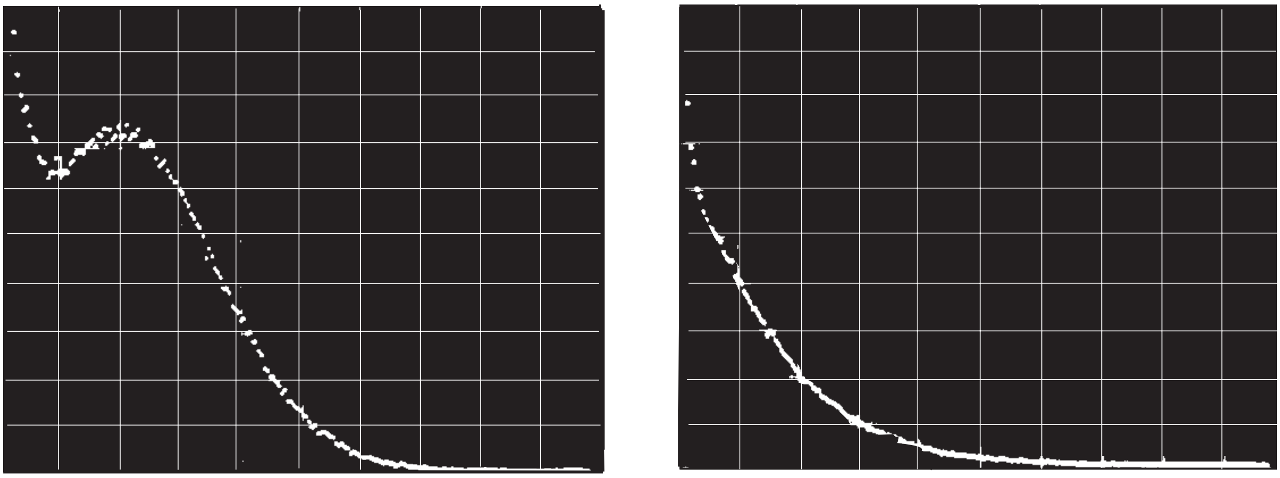


Fig.2.9 Example of dark current pulses on a wideband oscilloscope. Vertical axis, amplitude; horizontal axis, time



(a) (b)

Fig.2.10 Examples of dark-current pulse spectra (a) with linear-focusing CuBe dynodes, and (b) with venetian blind dynodes. Vertical axes, pulse frequency; horizontal axes, pulse amplitude

If the dark pulses were mainly due to single-electron thermionic emission from the cathode, their spectrum would be typical a single-photoelectron spectrum (§3.2.5). In fact, this is never the case so thresholds are always used to suppress unwanted pulses.

A commonly specified photomultiplier characteristic is the mean dark pulse rate, measured at a specific gain and temperature and with reference to a specific threshold. A threshold of about 1/4 of the mean peak amplitude is often used.

2.4 Energy resolution

An important application of photomultipliers is scintillation counting (Chapter 6), one objective of which is to measure the energy of nuclear radiations. The photomultiplier is coupled to a scintillator which emits light pulses in response to α-, β- or γ- radiation, the average quantity of light per pulse being proportional to the radiation energy dissipated in the scintillator. The mean anode charge per pulse is proportional to the quantity of light and, hence, also to the energy dissipated.

This proportionality holds only on average, however. For equal quantities of energy dissipated in the scintillator, the quantity of light that actually reaches the photomultiplier cathode fluctuates from pulse to pulse, as does the generation of photoelectrons, the collection efficiency, and the gain of the photomultiplier. Taking all this into account, the energy resolution of the scintillator/photomultiplier combination is given by

$$R_e = \frac{\Delta q_{a,s}}{\overline{q}_{a,s}} \tag{2.14}$$

where $\Delta q_{a,s}$ is the FWHM of the probability distribution of the anode charge fluctuations and $\overline{q}_{a,s}$ is the mean anode charge per pulse. The energy resolution (also called *pulse height resolution* or PHR) is a measure of a scintillation counter's ability to discriminate between closely similar pulses; it varies approximately as $1/\sqrt{E}$, where E is the radiation energy dissipated in the scintillator. (As is shown in Chapter 3, energy resolution is closely related to the noise which sets an ultimate limit to the accuracy of measurements made with scintillation counters.)

Energy resolution is a characteristic of a scintillation counter as a whole, not of a photomultiplier by itself; the contributions of the scintillator and photomultiplier are not independent of each other and cannot be treated separately. In photomultiplier data sheets, therefore, when energy resolution values are given, the type and dimensions of the scintillator with which they were measured are also specified, as is the type of radiation. Sometimes the energy resolution is measured against more than one type of radiation; for example, the 662 keV γ-radiation of ^{137}Cs, the 122 keV γ-radiation of ^{57}Co, and the 5.9 keV X-radiation of ^{55}Fe. Note that the lower the gamma energy, the better is the test for judging the photomultiplier energy resolution characteristics. At higher energies (662 keV), the test is dominated by the scintillator quality and gives little information about the photomultiplier contribution to the energy resolution.

2.5 Measurement of the characteristics

2.5.1 Cathode sensitivity

The cathode luminous sensitivity for white light is measured using a 2856 K tungsten-filament lamp calibrated for luminous intensity in a specific direction. With the cathode at a distance d from the lamp (Fig.2.11), the incident flux Φ_v is calculated from

$$\Phi_v = \frac{I_v A}{d^2}$$

where I_v is the calibrated intensity of the lamp and A the area of the cathode. After subtracting the cathode dark current from the measured cathode current, the luminous sensitivity S_k is calculated from Eq.2.2.

To ensure that the electric field is the same as in normal operation, the input system electrodes and at least the first two dynodes are operated at their normal voltages. The other electrodes are strapped so that the gain is low and a measurable cathode current can flow without causing excessive anode current. To ensure that the measured current is stabilized in the saturation region, the cathode-to-first-dynode voltage is set at about 100 V.

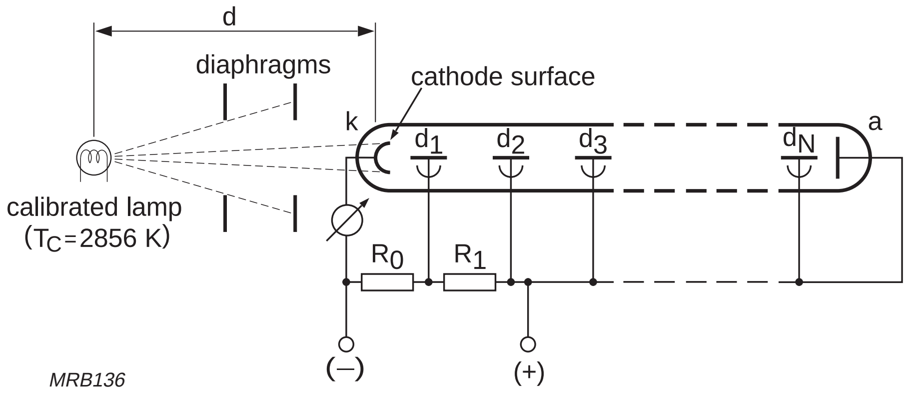


Fig.2.11 Set-up for measuring cathode sensitivity

To measure the cathode radiant sensitivity at a specific wavelength the calibrated lamp is replaced by a monochromatic source; for instance, a tungsten-filament or mercury vapour lamp combined with interference filters, or a monochromator. The radiant flux at the cathode is usually measured with a thermopile, precautions being taken to eliminate spectral leaks due to imperfections of the interference filters. The effect of such leaks can be significant because of the wide bandwidth of the thermopile and possible fast variations in flux density of the light source. To avoid problems, the interference filters may be augmented by high-pass or low-pass filters.

The measurement of radiant sensitivity is always difficult, and it is usually necessary to compare the results with those obtained by other means. For instance, the measured radiant and luminous sensitivities can be compared via conversion factors calculated from the relative spectral sensitivity characteristics of the cathode. The known emissivity characteristics of tungsten make it possible to calculate the flux transmitted through a given filter by a calibrated 2856 K lamp. Another way of cross-checking the measurement is with other photomultipliers with the same type of cathode calibrated as secondary standards.

Precautions must also be taken against the effects of cathode resistivity (§4.5.2). If the resistivity is high, the incident flux must be attenuated by calibrated neutral-density filters.

The uncertainty of radiant sensitivity measurements is seldom less than 5%.

2.5.2 Gain

Direct measurement of gain is usually practical only for low values ($G < 10^4$) because the anode current must not be allowed to exceed a certain maximum. Higher gains must be measured indirectly or in stages. Several acceptable methods are described in IEC Publication 306-4; the one generally used is described below.

First, as with the measurement of cathode sensitivity, the tube is connected with only the input system electrodes and the first two dynodes at their normal voltages, and the cathode dark current is measured. Then the tube is exposed to an accurately reproducible flux and the corresponding cathode current I_k is determined by subtracting the dark current from the measured current. Next, the tube is reconnected normally and the anode dark current is measured. The tube is then exposed again to the same flux as before, but with neutral density filters in the light path to attenuate it by a known factor F, and the corresponding anode current I_a is determined. The gain is then

$$G = \frac{I_a}{I_k} F \qquad (2.16)$$

due to excitation of energy levels in the glass window and the photocathode layer. If the incident flux is accurately known, the anode sensitivity can be evaluated directly, using Eq.2.9 or 2.10.

2.5.3 Dark current

To measure the dark current the tube is enclosed in a chamber (e.g. as described in IEC Publication 306-1) that excludes all radiation, visible and invisible, in the sensitivity range of the cathode. The current is measured with a galvanometer in the anode circuit (Fig.2.12). If the tube were connected in normal polarity, the galvanometer would be at a high voltage with respect to ground and leakage currents to ground in the instrument could cause significant error. Therefore the tube is connected in negative polarity (anode grounded, cathode at high negative potential), although this necessitates special precautions:

- the tube envelope must be perfectly insulated from its surroundings, particularly surrounding metal at ground potential, to prevent any leakage that might provoke dark current instability.
- considerable time must be allowed for the dark current to stabilize after the high voltage is applied (much more time than when the tube is connected in normal polarity, see Fig.3.6). The more recently the tube has been exposed to light, the more important – and the longer – the stabilization time (§3.1.5 and 3.1.6); tubes with exceptionally low dark current may require several hours (up to 24 hours). If the high voltage is altered during the measurement procedure, time must again be allowed for the dark current to stabilize at the new voltage.

Other precautions must also be taken to reduce leakage currents which may be significant in comparison with very low dark currents (less than a nanoampere):

- the socket and base of the tube must be perfectly clean and free of any trace of moisture; leakage currents on the socket can be measured by applying the high

voltage with the socket empty. Likewise, all connections must be perfectly clean, with no trace of grease or moisture.
– the insulation of the anode lead must be of very high quality (e.g. teflon, diallylphthalate). To minimize piezoelectric effects which could superimpose spurious currents on the dark current, a low capacitance lead should be used.

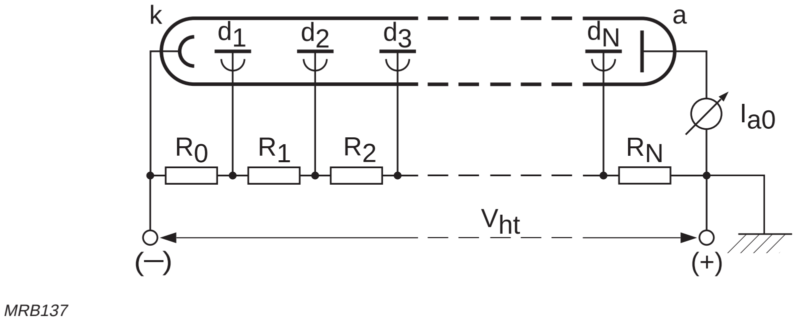


Fig.2.12 Dark-current measurement; the tube is connected in negative polarity with (+) supply terminal grounded.

2.5.4 Dark pulse rate

Figure 2.13 shows a set-up for measuring the dark pulse rate; the tube can be connected in positive polarity, because the leakage currents, being DC, are blocked by the capacitor. In positive polarity the dark current stabilizes quickly. It is still advisable, however, to keep the tube in total darkness for several hours (for example overnight) before the measurement, especially if it has recently been exposed to light.

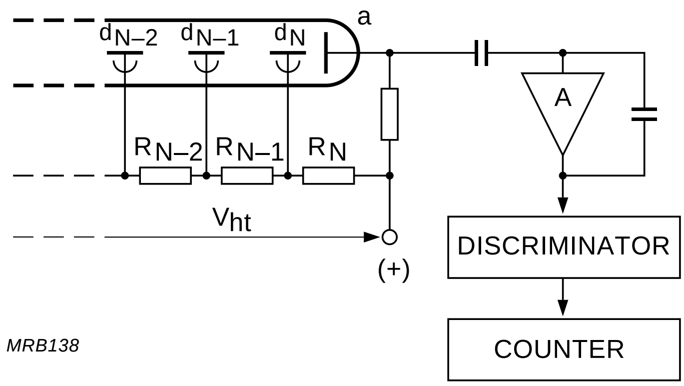


Fig.2.13 Dark-pulse-rate measurement

The dark pulses are integrated in a charge-sensitive amplifier and converted into voltage pulses that are fed to a discriminator, the threshold of which is set so that only pulses that correspond to a charge exceeding a certain level will be counted. In the spectra of Fig.2.10, for example, the chosen threshold might be a quarter of the amplitude corresponding to the centre of gravity of the single-electron distribution; that is, a quarter of the mean anode-pulse amplitude that would result from a single photoelectron (popularly referred to as 'a ¼ photoelectron').

By applying a voltage pulse U(t) to a capacitor C at the input, the discriminator can be calibrated from the relation

$$q(t) = C \int_0^t U(t)\, dt$$

2.6 Interpretation of data

The information presented in photomultiplier data sheets is ranged under the following subdivisions and headings.

General description. As an aid to making a preliminary choice, this gives general information about size, construction, photocathode, and intended applications.

General characteristics. Details of window, photocathode and electron optical input multiplier system.

Recommended voltage dividers. Divider networks for alternative voltage distributions (§5.2).

Output characteristics. Gain or anode sensitivity, dark current, time characteristics, energy resolution, behaviour in a magnetic field, and linearity and stability parameters. In some cases these are given for alternative voltage distributions to enable the user to optimize specific performance aspects for an intended application.

The qualification *typ.* (typical) preceding a value means that it is derived from measurements on a representative sample and corresponds to the 50% point (median value) of the cumulative relative frequency curve for the sample. Values marked *typ.* may vary slightly from sample to sample; such values are always accompanied by an upper or lower limit defining the acceptability limit for the tube. Measured actual values for each tube are entered in an individual characteristics sheet which accompanies the tube and usually gives:

- the cathode luminous, CB filtered or radiant sensitivity
- the supply voltage required for obtaining a specified gain or anode sensitivity
- the dark current at that value of gain or anode sensitivity. The sign ≈ or the qualification *approx.* preceding a value means that the value is determined by regular sampling from production; for example, certain time characteristics that vary very little from tube to tube of a given type.

Limiting values (Absolute maximum rating system). These are limits for voltages, gains currents, and temperatures that the user must observe to avoid damaging the tube. Where stated limits for different operating parameters cannot be applied simultaneously, the most restrictive should be observed. For example, if the maximum voltage were applied to each stage of a photomultiplier, the maximum gain for the tube as a whole would be exceeded; thus the latter takes precedence.

Notes. These refer to the output characteristics and specify either the definitions of certain terms or the conditions for measuring certain characteristics.

Performance curves. These include spectral sensitivity characteristics and such other characteristics as gain, anode sensitivity and dark current, as functions of supply voltage.

Mechanical data. Dimensions, mass, base designations, and base-pin identification.

Accessories. Type numbers of sockets etc.

The Photonis photomultiplier catalogue contains an introductory section which further defines the terms used in the data and describes generally applicable methods and conditions for measuring photomultiplier characteristics. It also discusses considerations relating to such factors as noise, linearity and stability, and includes operating notes regarding power supply, pulsed and continuous operation, and precautions to be taken to ensure accuracy, minimize dark current and maximize useful life. Individual data sheets are also available for each type.