TIME AND MEASUREMENT

BY ANTHONY H. SMITH

PART TWO: THE UCT : SIGNAL PROCESSING AND THE INPUT CIRCUITS

Our series on universal counter timer continues with an examination of the important aspects of trigger signal conditioning and input protection.

Before the digital processing circuits of the Universal Counter/Timer (uct) can begin to measure the frequency and time parameters of an electrical signal, it is first necessary to convert the signal to digital form. This is the task of the input conditioning circuits which constitute the analogue processing section of the uct.

A digital signal is basically a series of rectangular pulses having the same constant amplitude. However, the shape and size of the input signal may vary enormously from one signal source to the next; furthermore, the presence of noise and interference may grossly distort the fundamental waveform.

Consider, for example, the signal shown in Fig. 1, where we wish to measure the period τp. Feeding the signal directly to the main gate would almost certainly prove disastrous due to the 100V dc offset voltage. AC coupling can remove this offset, but the signal amplitude itself is too large for the digital components to handle.

However, attenuating the signal by a factor of ten will bring the amplitude down to a safe level; we can now feed the signal to the main gate and take a reading — right?

Wrong! The uct is just as likely to measure the time $\tau\chi$, caused by the noise spike, as it is the correct parameter, τp. It might also display τy, the period of the superimposed signal, or may even attempt to measure all three time periods, resulting in a randomly changing readout. Fortunately, further processing such as filtering and trigger level adjustment enables the counter to "pick out" the required parameter from the mass of superfluous information.

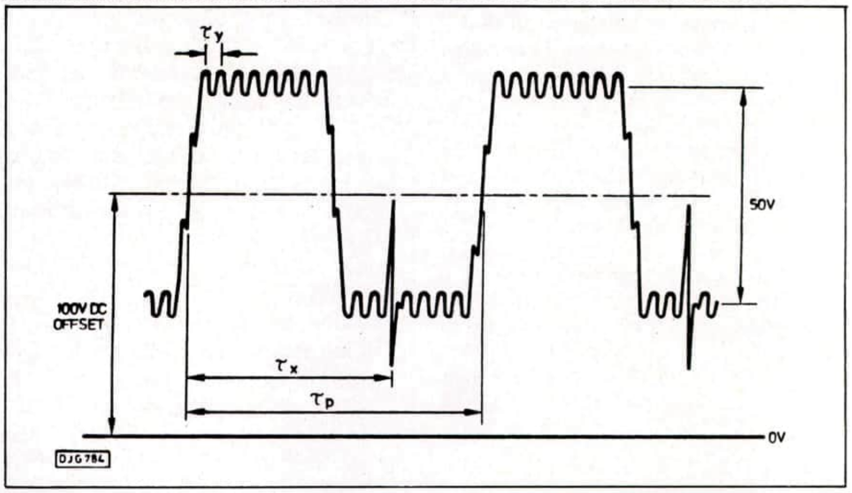


Fig.1. *Complex input signal*

Obviously, the more sophisticated the input circuitry, the more selective becomes the instrument's operation, enabling us to measure a wide variety of signals — hence, the "universal" counter/timer.

INPUT CIRCUITRY

A comprehensive input processing circuit is represented in Fig. 2. This arrangement is capable of conditioning signals in the frequency range dc–100MHz, and is typical of the analogue circuitry found in good quality counters.

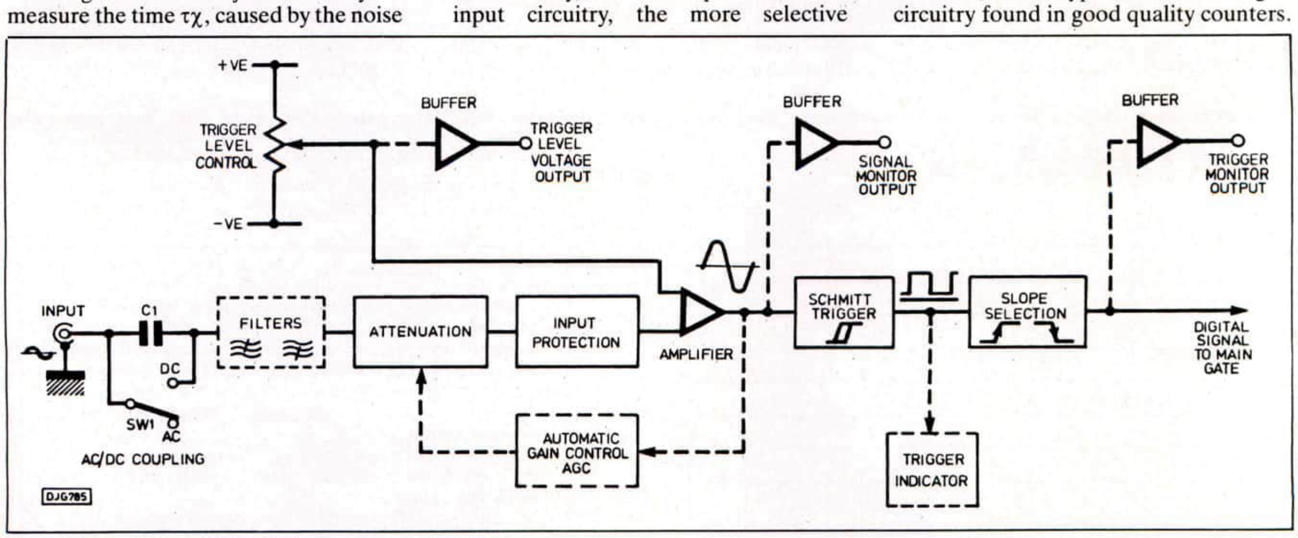


Fig.2. *Typical dc – 100MHz input processing circuitry*

Circuits may differ from one model to the next, but they should all provide adjustable attenuation, protection components to guard against overload, an amplifier, and a Schmitt trigger (to convert the analogue signal to digital form). Additionally, the trigger level and slope controls are necessary for selecting the precise points on the input waveform where the measurement begins and ends.

HYSTERESIS

The Schmitt trigger is a voltage comparator with hysteresis, an essential property which allows it to "ignore" the noise content of a signal such that only the fundamental waveform itself is converted to digital form.

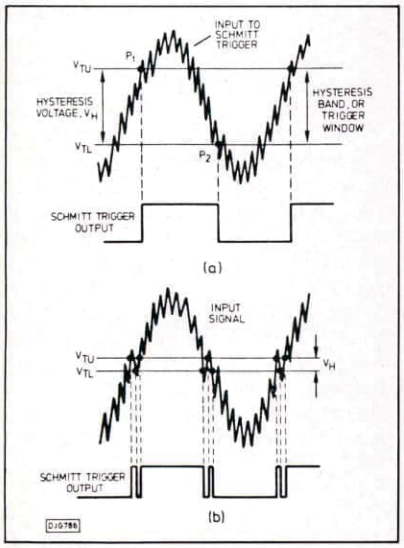


Fig.3. *(a) Schmitt trigger operation (b) Narrow hysterisis band*

The purpose of the trigger is to produce a step output when the input signal crosses one of two threshold voltages — see Fig. 3a. For example, when the input crosses the upper threshold voltage, V_{TU}, at point P_1, the Schmitt output rapidly changes state. However, subsequent crossings of this threshold due to the superimposed noise have no effect, and it is not until the signal crosses the lower threshold voltage, V_{TL}, at point P_2, that the output changes state again.

The difference between the upper and lower threshold voltages is the hysteresis voltage, V_H, sometimes called the "hysteresis band", or "trigger window". Note that the input signal must cross *both* threshold levels for the Schmitt to produce a corresponding digital output signal. Obviously, if the trigger window is too narrow, as in Fig. 3b, the noise itself will trigger the output and cause erroneous measurements.

The question is then, how wide should we make the trigger window? The situation of Fig. 3b suggests it be made as wide as possible so as to minimise the effects of noise (the trigger window is sometimes referred to as the "noise immunity band"). However, the wider the trigger window, the greater must be the input signal amplitude in order to cross both thresholds: in other words, increasing the hysteresis voltage has the desirable effect of increasing the noise immunity, but at the expense of diminished input sensitivity. (The sensitivity of the uct is the smallest signal amplitude which can be detected).

Unfortunately, the situation is further complicated by the conflicting requirements of frequency and time measurements. When measuring frequency, the hysteresis voltage should be just less than the peak-peak voltage of the input signal — in this way, signals buried in noise can be detected and measured.

However, for certain time measurements the trigger window should be very narrow to reduce the errors caused by differences in the input signal rise- and fall-times. This is illustrated in Fig. 4, where the parameter of interest is the pulse width.

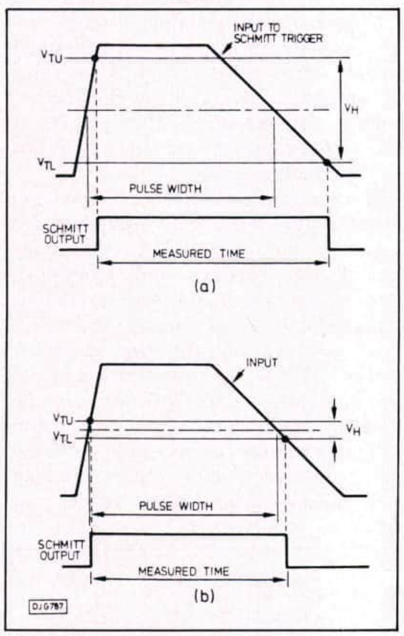


Fig.4. *Time measurement errors*

In Fig. 4a, the wide hysteresis band leads to a measured time which is considerably longer than the actual pulse duration. However, by narrowing the band (Fig. 4b) the Schmitt output is made almost equal to the pulse's width.

An obvious solution to these problems would be to provide a variable hysteresis band which could be adjusted to suit the prevailing signal and measurement conditions. However, an assortment of components is usually responsible for setting the threshold levels, and so a simpler alternative is to vary the input signal amplitude, noise and all, by means of attenuators. Obviously, reducing the signal amplitude has exactly the same effect as *increasing* the hysteresis band. Consequently, the upper and lower Schmitt thresholds can now be fixed such that the hysteresis band is constant, and is symmetrical about zero volts.

The magnitude of the hysteresis band dictates the sensitivity of the instrument: a hysteresis voltage of, say, 10mV would allow signals as small as 10mVpeak-peak (3.5mV rms) to be detected. However, the thresholds cannot be set too close together or the trigger will become unstable due to ageing, supply-voltage drift, and temperature changes. Furthermore, any offset voltage at the trigger input may significantly bias a small hysteresis voltage. Consequently, most triggers have a relatively large hysteresis band, but are preceded by an amplifier to achieve the same sensitivity: for example, a hysteresis voltage of 100mV (ie, V_{TU} = +50mV, V_{TL} = −50mV) and an amplifier gain of ten result in a sensitivity of 10mVpeak-peak.

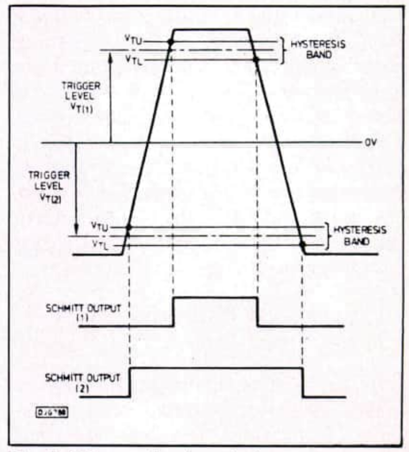


Fig.5. *Trigger level variation*

TRIGGER LEVEL

The analysis of the Schmitt trigger has assumed the trigger level (the mid-point of the hysteresis band) to be fixed at zero volts. However, many time measurements require that we "shift" the trigger level relative to the input signal, such that the trigger points can be fixed at almost any place on the waveform. This is exemplified in Fig. 5, where the trigger level is initially set positive, $V_T(1)$, and then negative, $V_T(2)$, to measure the pulse width at different places on the input signal.

Varying the trigger level is equally useful for eliminating the problems caused by large-amplitude noises, such as the spikes seen earlier on the signal in Fig. 1.

Often, the simplest way to vary the trigger level is not to shift the hysteresis band, but instead to shift the amplifier output signal while keeping the hysteresis band symmetrical about zero volts. This is achieved by adding a dc offset to the amplifier output: for example, shifting the output signal *negative* by two volts has exactly the same effect as moving the hysteresis

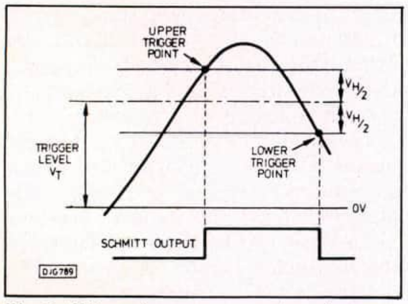


Fig.6. *Triggering occurs at the trigger points*

band *positive* by two volts, ie, a trigger level of +2 volts.

This ability to locate the trigger points anywhere on the waveform is all very well, provided we know just where we are setting them. Indeed, the precision of time measurement (such as that in Fig. 5) depends mainly upon the accuracy with which we can set the trigger points, rather than on the accuracy of the measurement circuitry itself. Remember, also, that triggering occurs not at the trigger *level*, but at the trigger *points* — see Fig. 6. Ideally, it would be best to measure directly the trigger point voltages. However, this is not possible since they do not exist as nodes anywhere in the circuit; instead, we must measure the trigger level voltage and then add or substract half the hysteresis voltage. That is:

Upper Trigger Point $= V_T + V_H/2$
Lower Trigger Point $= V_T - V_H/2$.

In several ucts, a voltage equal to the trigger level (for example, that at the wiper of the trigger level pot) is output such that V_T can be read directly on a dvm. Knowing V_H (which should be given in the counter's specifications) we can now establish the exact trigger points using the equations above. Incidently, some of the more sophisticated ucts incorporate the dvm into the instrument itself; for example, the Philips PM6652 uses a special technique known as "hysteresis compensation" such that the trigger points themselves can be read directly from the instrument's display.

The trigger level range is an important specification which differs considerably from one counter to another. Obviously, the greater the range the more versatile a measurement can be. Varying the trigger level over a ± 5V range is usually more than adequate; however, on some models the range may be as small as ± 1V, or less.

When making frequency measurements on signals symmetrical about zero volts, the trigger level offset is not required since the best sensitivity is obtained with the hysteresis band centred on zero volts: consequently, many trigger level controls have a detent, or "preset", position which sets the trigger level at exactly zero volts.

THE AMPLIFIER

Provided the trigger window is not excessively wide, an amplifier gain in the region of 20dB is usually sufficient to provide an input sensitivity of around 5mV rms (a typical value for most good-quality counters). However, the gain must be very carefully set if we are to have any confidence in adjusting the trigger level. (This important requirement will become clearer when we look at the input attenuators).

Furthermore, the gain must remain stable over the counter's frequency range, ie, we require a flat frequency response, otherwise the sensitivity will deteriorate at those frequencies where the gain falls. Since most counters have a frequency range from dc to at least 10MHz, the amplifier must be a wideband device: additionally, a very high slew-rate (at least 100V/Ωs) is essential for good pulse response. However, fast slewing alone does not guarantee a perfect pulse output, and the amplifier must be carefully compensated to avoid excessive overshoot and ringing.

Several other demands are made of the amplifier. For example, it must be a low-noise design, especially if very small signals are to be detected. Also, since the amplifier is dc coupled to the Schmitt trigger, any unwanted offset voltage at the output must be very small so as not to bias the trigger level voltage.

The amplifier's output voltage swing dictates the dynamnic input voltage range of the counter. This important specification defines the amplifier's *linear* range of operation. Any input signal which forces the amplifier into saturation is outside the counter's dynamic range. However, because the dynamic range refers to the *input* signal, it does not necessarily equal the saturation limits: as we shall see later, the amplifier gain and selected attenuation must also be taken into account.

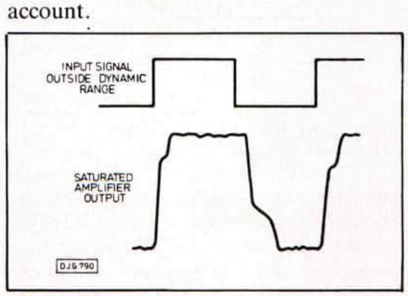


Fig.7. *Effects of exceeding the dynamic range*

Typical effects of exceeding the dynamic range are shown in Fig. 7, where the distortion caused by amplifier saturation will corrupt a variety of measurements, particularly pulse width, time interval, and transition time. Note, also, that the dc content of an input signal may cause saturation, *unless* ac coupling is selected.

Like oscilloscopes and voltmeters, the uct must have a high input impedance so as to minimise the load on the signal source, and consequently the amplifier input must have a high resistance and low capacitance. For most counters, an impedance of 1M in parallel with 30pF or less is typical; however, because the amplifier is a wideband device, the high input impedance makes it particularly sensitive to noise, and careful screening of the input circuitry is necessary to minimise false triggering.

HOW MUCH ATTENUATION?

The purpose of the input attenuators is two-fold: firstly, they allow large-amplitude signals to be reduced such that they are within the dynamic range of the counter; secondly, they provide a means of varying the signal amplitude in relation to the trigger window. Unfortunately, the amount of attenuation required varies considerably with the input signal amplitude and the type of measurement being made.

Consider, for example, making a measurement on a signal with a peak-peak amplitude of 5V, and assume the input amplifier has a gain of ten and a maximum output voltage swing of ± 5 volts. Obviously, feeding the signal directly to the amplifier will cause it to saturate. However, if the signal is first attenuated by a factor of ten, the "overall gain" (ie, the amplifier gain combined with attenuation) will be unity, and the amplifier output will have the same amplitude as the input signal. In this case, the dynamic input range is 5V p-p, and the trigger level range is ± 5V.

If, now, the attenuation is increased to x100, the overall gain is reduced to 0.1, and the dynamic input range and trigger level range are increased to 50V p-p, and ± 50V, respectively. In other words, any trigger level in the range − 50V to + 50V can be set on an input signal having a maximum amplitude of 50V p-p.

In general, the dynamic range equals the magnitude of the trigger level range (although on some models the trigger level range is somewhat less than the dynamic range) and:

$$\text{Dynamic Input Range (volts p-p)} = \frac{\text{Amplifier Output Voltage Range}}{\text{Amplifier Gain}} \times \text{Attenuation Factor}$$

Note that the trigger level range (and the dynamic range) *relative to the amplifier output* remains constant irrespective of the attenuator setting, and this should be borne in mind if the trigger level is output and read from a voltmeter. Note, also, that the amplifier gain and the attenuation factor must be accurately set in order to establish the

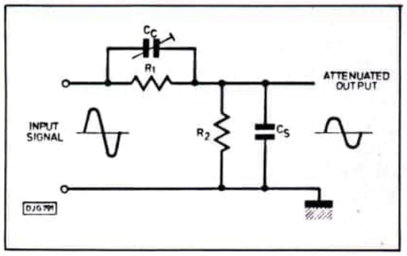


Fig.8. *Compensated attenuator*

corresponding dynamic and trigger level ranges.

Frequency compensated step attenuators are particularly suitable since the attenuation factors can be precisely set and remain constant at all frequencies. An example is shown in Fig. 8, where R1 and R2 form a simple potential divider. These resistors are chosen not only to give the desired attenuation, but also to provide the correct input resistance to the counter. For example R1=900k and R2=100k result in an attenuation of x10, and an input resistance of 1M. For x100 attenuation, R1 would need to be 990k, and R2 10k.

In practice, some stray capacitance, Cs, always exists in shunt with R2. For sinusoidal inputs, this results in increased attenuation at high frequencies since R1 and Cs effectively form a low-pass filter.

For high-frequency pulse inputs the effect is more dramatic: Fig.9 shows how Cs integrates the input pulses leading to gross signal distortion.

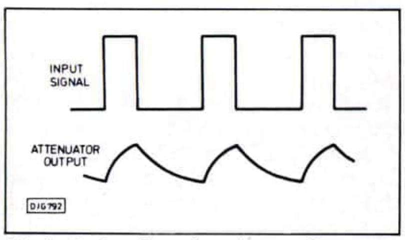


Fig.9. *Pulse distortion due to Cs*

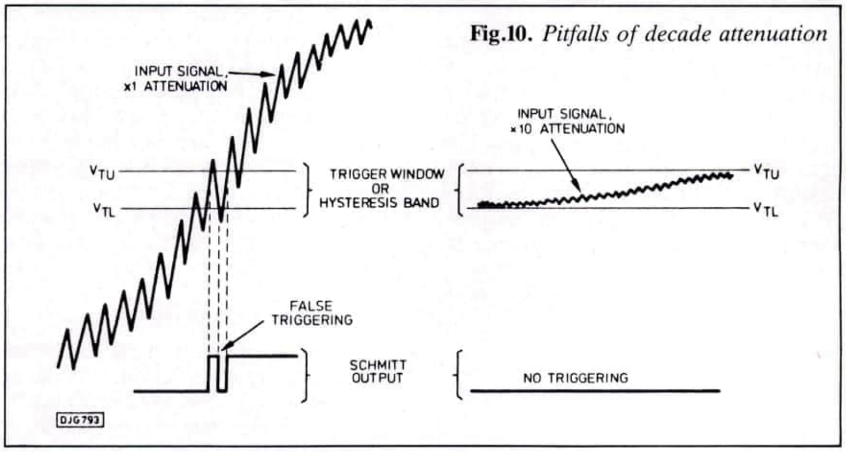
To compensate for the effects of Cs, a trimmer capacitor, Cc, is added in shunt with R1. By adjusting Cc such that the ratio of its reactance to that of Cs is equal to the ratio of R1/R2 (ie, XCc/XCs = R1/R2), the attenuation is made frequency independent. Consequently, all signals are passed with constant attenuation, and the rectangular shape of pulse inputs remains intact whatever the frequency.

Note that Cc in series with Cs constitute the counter's input capacitance, which should not exceed 30 – 40pF for any attenuator setting. In this way, the counter's input impedance remains constant, even though the attenuation may be switched from x1 to x10 to x100, etc.

Although step-type attenuation is best for measurements requiring precise setting of the trigger level, it does have drawbacks. Consider, for example, a counter which has x1, x10, x100 attenuation with corresponding dynamic ranges of 500mV p-p, and 50V p-p, respectively. If the input signal is 600mV p-p, which attenuation setting do we choose? Obviously, x1 attenuation (ie, no attenuation) will not do, since the corresponding range is too small. Consequently, x10 attenuation must be chosen, even though most of the dynamic range (5V p-p) will be "wasted" on the small input signal.

This example introduces an important consideration, namely that increasing the attenuation is equivalent to *increasing the trigger window relative to the input signal*. In this respect, decade attenuation is often too severe; this is exemplified in Fig.10, where x1 attenuation produces false counts, and x10 attenuation results in no measurement at all.

Fig.10. *Pitfalls of decade attenuation*



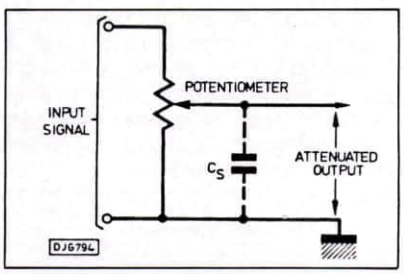


Fig.11. *Variable attenuation*

Obviously, some kind of continuously variable attenuation is required, such as that provided by the potentiometer in Fig.11. Unfortunately, this attenuator also has limitations. Firstly, it is practically impossible to compensate for the stray capacitance, Cs; consequently, more high-frequency roll-off is introduced as the attenuation is increased. Secondly, there is no way of knowing the exact relationship between the trigger level voltage and the input signal, since the relationship varies as the potentiometer is adjusted.

For these reasons, the variable attenuator is of little use for most time measurements. However, for sinusoidal frequency measurements (where the trigger level is usually zeroed, anyway) the potentiometer comes into its own, especially for extremely noisy signals where the amplitude can be gradually reduced until only the fundamental signal itself crosses the hysteresis thresholds.

In order to get optimum measurement conditions, many ucts offer both continuously variable and step-type attenuation. An interesting example is found on the Philips PM6670 range of counter/timers. These models feature a switchable x10 attenuator, along with a potentiometer type which doubles as the trigger level control when making time measurements.

Note that whichever type of attenuation is employed, the instrument sensitivity varies accordingly: for example, a counter with 10mV sensitivity at the x1 attentuator setting will not be able to detect signals less than 1 volt when x100 attenuation is being used.

INPUT PROTECTION

With x1 attenuation selected, the input signal is fed directly to the amplifier, making some form of overload protection essential. A voltage limiting scheme typical of many counters is shown in Fig.12. This is a simple voltage clipping circuit when an excessive input signal causes D1 or D2 to become forward biased. Consequently, the amplifier input voltage, V_{IN}, cannot increase beyond either supply rail, and practically all of the large overload voltage is dropped across R1.

Obviously, the resistance of R1 must be large enough to limit the input overload current which flows through the parallel combination of D1 (or D2) and the amplifier input impedance. If R1 is, say, a 120k, 0.5W component, the input current caused by a 250V rms overload will be limited to a safe value of 2mA rms (3mA peak).

With the counter set at x1 attenuation, $R1+R_A$ is effectively the counter's input resistance, typically 1M. Thus, if R1=120k, R_A must be 820k. However, if the amplifier has fet inputs, R_A may be several hundred megohms, making the amplifier highly vulnerable to noise: consequently, a shunt resistor must be added across R_A to bring the counter's input resistance down to 1M.

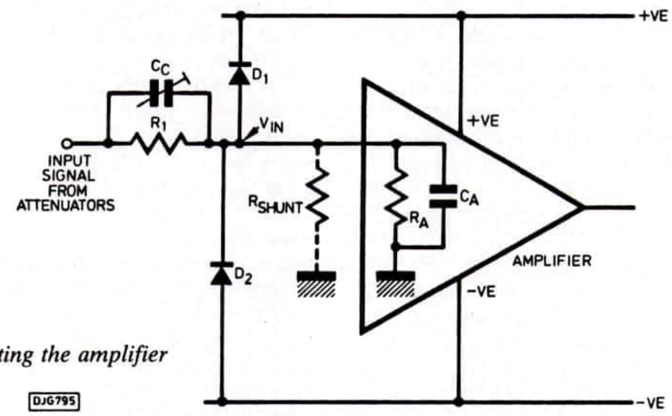


Fig.12.
Protecting the amplifier

Note that R1 forms a potential divider with R_A such that the input signal is slightly attenuated; this is easily remedied by increasing the amplifier gain accordingly. However, the amplifier's input capacitance, C_A, is more of a problem, making it necessary to compensate the network by adding Cc across R1. Unfortunately, the low reactance of Cc at high frequencies means the protection afforded by R1 is lost; as a result, the maximum input voltage becomes frequency dependent, as shown in Fig.13.

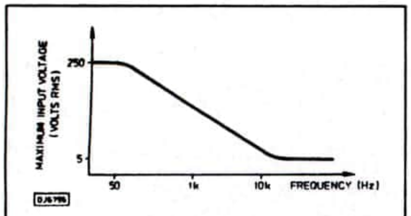


Fig.13. *Frequency dependent protection*

Most instrument manufacturers specify the damage level (the maximum tolerable input voltage) for various frequencies, or may illustrate it graphically as in the figure.

Fortunately, the frequency dependence is rarely a problem since most high voltages are confined to the mains frequency range, although care must be taken when working with the likes of high-power, high-frequency transmitters.

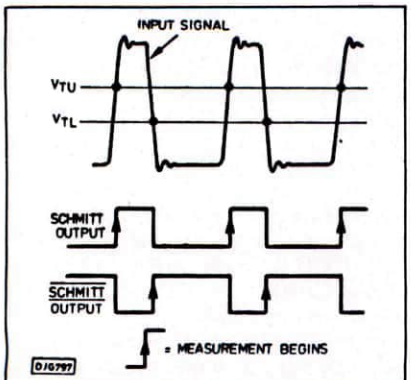


Fig.14. *Effect of slope control*

SLOPE SELECTION

The slope control is a two-position switch which allows the operator to choose whether the measurement begins on the rising or falling edge of the input waveform — see Fig.14. Basically, the switch position determines whether a true or inverted Schmitt output is fed to the main gate; although this has no effect on frequency and period measurement, it provides considerable versatility when measuring pulse width or the time interval between two events.

AC OR DC COUPLING?

AC coupling is required when measuring a signal with a relatively large dc offset, and is achieved by opening S1 (Fig.2) such that only the ac component is coupled via C1.

However, the combination of C1 (typically $0.1\mu F$) and the counter's input resistance, R_{IN}, effectively forms a high-pass filter; consequently, ac coupling cannot be used on signals which vary slowly with time, since these are greatly attenuated and/or distorted.

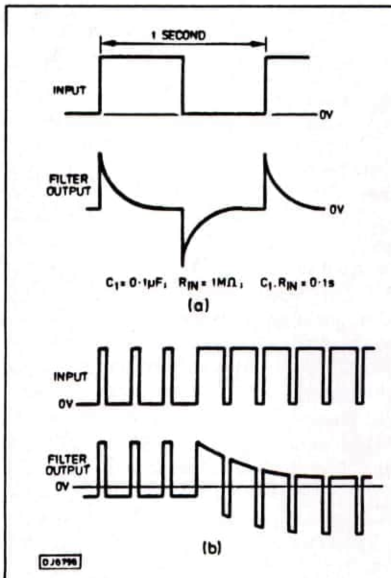


Fig.15. *Signal distortion due to AC coupling*

AC coupling can have serious effects on digital signals. Consider the example in Fig.15a, where the period of the input is much longer than the time constant ($C1.R_{IN}$) of the filter. Note how the filter differentiates the signal, making it difficult to measure anything but the frequency or period of the input.

With AC coupling, any change in the digital signal which affects the average dc level (such as changes in duty cycle or transition time) may cause considerable signal distortion. Fig.15b shows how a change in duty cycle makes it impossible to set constant trigger points on the ac coupled waveform.

Obviously, great care is needed when a digital signal is ac coupled, and in many cases the correct measurement can only be made by combining dc coupling with judicious use of the trigger level control.

It is for the above reasons that all sections of the input circuitry are *dc coupled*.

ADDITIONAL FEATURES

As well as the fundamental conditioning circuitry described so far, many counters feature additional sections to enhance the signal processing or to provide some degree of user feedback.

FILTERING

A typical example is the use of filters which may be switched in to help "clean up" the input signal. These filters reject a particular range of frequencies, and are usually first-order rc types with 20dB per decade roll-off. For example, a low-pass filter with a 3dB-frequency of 50kHz is useful for removing high frequency noise from audio signals.

A high-pass filter, on the other hand, might have a break frequency around 1kHz such that 50Hz mains interference can be removed. A typical application for this filter is shown in Fig.16, where a high frequency signal is superimposed on the large-amplitude mains hum: the hf signal can only be measured by filtering out the 50Hz interference.

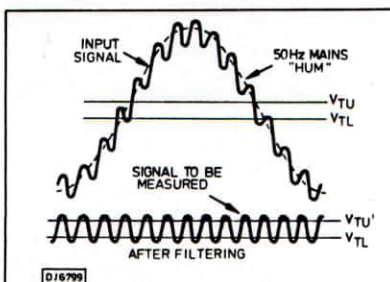


Fig.16. *Effective use of filtering*

VISUAL FEEDBACK

The commonest form of user feedback is the trigger indicator. In its simplest form, this is a led driven by the Schmitt output. In the presence of an input signal large enough to cross the hysteresis thresholds the led flashes at a rate equal to the input frequency; for small signals (or none at all), the led is extinguished.

An improvement on this theme is the "tri-state" led, which not only indicates input triggering, but also gives information about the trigger level. With the input correctly triggered the led flashes at a constant rate (typically about 3Hz); however, with the trigger level set too high or too low, the led is continually off or on, respectively. This is summarised in Fig.17.

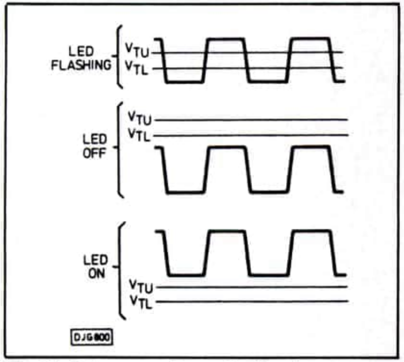


Fig.17. *Tri-state trigger indication*

Some of the more sophisticated ucts provide signal and trigger outputs (usually derived from a buffer with short-circuit protection) allowing the amplifier and Schmitt trigger signals to be monitored on an oscilloscope.

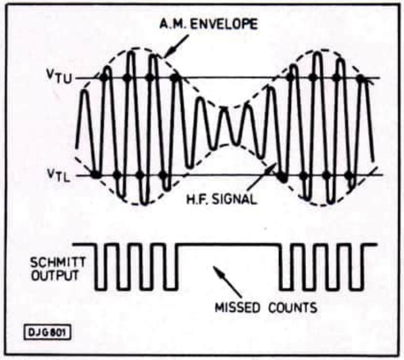


Fig.18. *Agc circuit – possible problems*

Superimposing the two signals gives a direct visual indication of trigger level adjustment, thus making it extremely easy to set the desired trigger points. Furthermore, the effects of ac coupling, filtering, and attenuation are also plainly visible.

AGC SIMPLIFIES OPERATION

Automatic gain control behaves as a "hands-off" sensitivity control, and is particularly useful when measuring the frequency of noisy inputs. By monitoring the amplifier output, the agc circuit automatically alters the input attenuation (or adjusts the amplifier gain) such that the signal level at the Schmitt trigger input is just greater than the hysteresis band. In this way, the overall gain is kept low enough to avoid false triggering due to noise.

However, agc does have limitations, particularly at low frequencies (50Hz or less) where it may respond "too quickly", effectively cancelling out the input signal.

Problems can also be encountered when measuring the carrier frequency of an amplitude modulated signal. Instead of following the hf signal, the agc loop may lock-on to the am envelope, such that many of the hf counts are missed — see Fig.18.

To avoid problems of this kind, the agc loop must be switched out, so that control of the attenuators is returned to the operator.

VERSATILITY AND ACCURACY

By now you may be a little surprised at the diversity and complexity of the input processing circuitry, and one could be forgiven for wondering whether it is all really necessary.

Remember, however, that appropriate signal conditioning is needed not only for versatility, but also for accuracy. We shall see in a future article that even the simplest uct time base oscillator can have an accuracy better than one part in 100,000: obviously, such accuracy is meaningless if the input signal cannot be correctly digitised. PE