FM DEMODULATORS FOR BTSC STEREO

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ABSTRACT

Of the many kinds of FM demodulators, two types have been commonly used to demodulate television aural carriers modulated with BTSC stereo: quadrature demodulators and pulse-count demodulators. These two types of demodulators are described. Waveform plots are used to illustrate the operation in a qualitative and intuitive way. The relative advantages and disadvantages are discussed. In particular, cost/circuit complexity, noise, and sources of distortion are considered in some detail. The effect of these parameters on BTSC stereo is discussed.

INTRODUCTION

Through the history of FM, several different types of circuits have been used for FM demodulation. Some, like discriminators and ratio detectors, were particularly appropriate to times when passive circuits were less expensive than active circuits. Others, such as phase-locked-loops, quadrature demodulators and pulse-count demodulators became practical with the availability of inexpensive transistors and integrated circuits.

The low FM threshold of the phase-locked-loop demodulator has made it popular in applications where carrier-to-noise ratio is marginal. In television transmissions, however, carrier-to-noise ratio is limited by video quality long before the audio approaches threshold.

Two types of FM demodulators have been widely used for recovering BTSC stereo; the quadrature demodulator and the pulse-count (or pulse-averaging) demodulator. This paper will concentrate on these two types of demodulators.

QUADRATURE DEMODULATORS

Figure 1a. shows a block diagram of a quadrature demodulator. The name quadrature comes from the fact that a network with a 90 degree phase shift at the carrier frequency is used. At the input of the demodulator, the signal is split into two paths. Part of the signal goes directly to one input of an AND gate or multiplier. The rest of the signal passes through the phase shift network before getting to the other input of the AND gate. The output of the AND gate is passed through an integrator to average the signal (low-pass filter it) and recover the baseband.

The effect of the phase shift network is shown in Figure 1b. The signal passing through the network is shifted in phase by an amount depending on its deviation ($\Delta\omega$) from the carrier center frequency (ω_0). A carrier at center frequency ($\omega - \omega_0=0$) is shifted by 90 degrees. A carrier at higher than center frequency is shifted by less than 90 degrees, and so on.

To illustrate how AND'ing the original signal with the phase shifted version provides FM demodulation, we consider three separate cases. Square waves are used for clarity.

- Figure 1c shows the case in which the instantaneous frequency (ω) is at the carrier center frequency (ω_0). The phase shift between the two AND inputs is the nominal 90 degrees. The output of the multiplier is HIGH whenever both inputs are HIGH as shown in the output pulse-train. After integrating we get the average voltage of the pulse-train as shown by the dashed line in the output waveform.

- Figure 1d shows the case in which the instantaneous frequency (ω) has been deviated to less than the carrier center frequency (ω_0) until the phase shift between the gate inputs is > 90 degrees. The pulse-train out

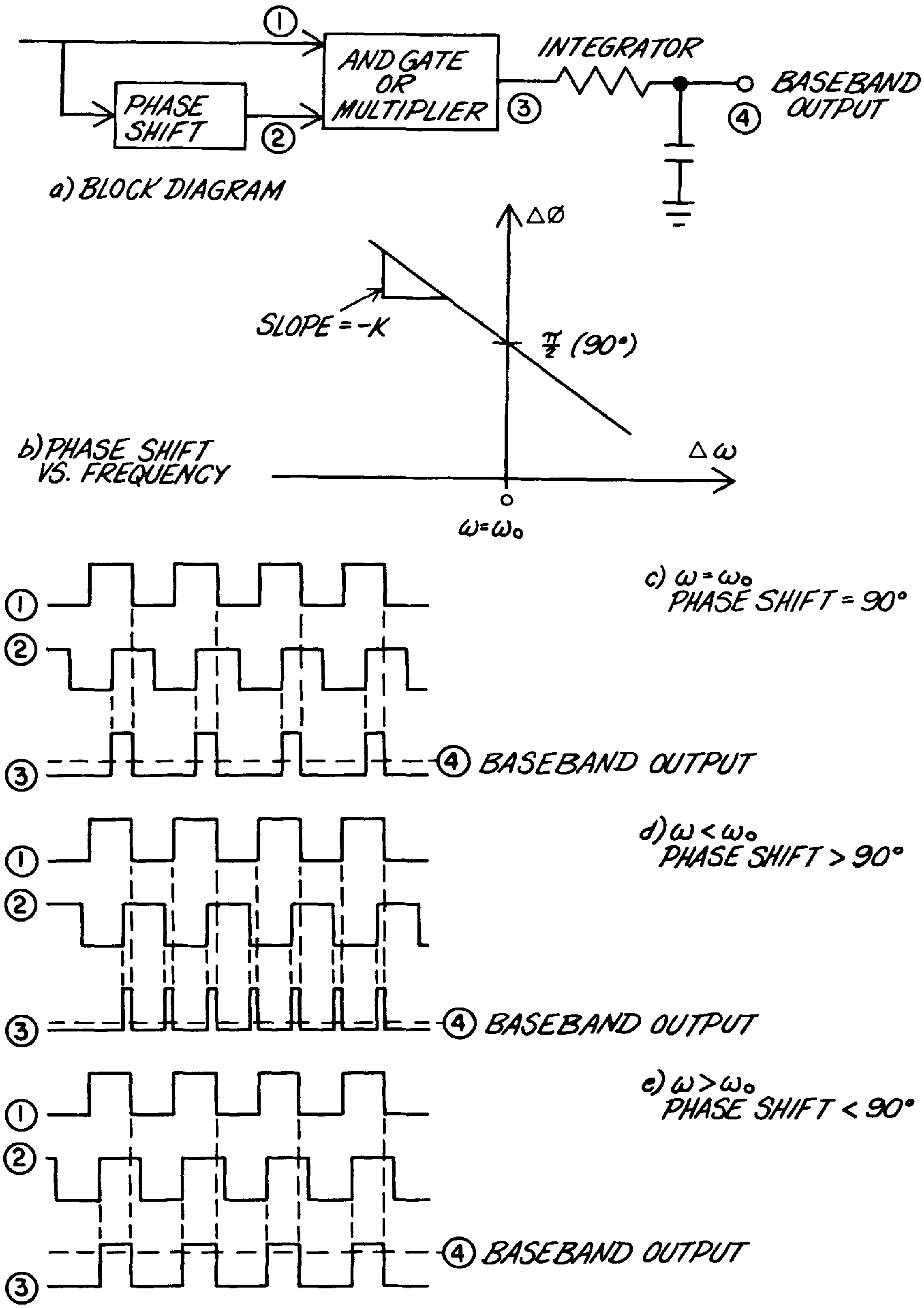


FIGURE 1. QUADRATURE DEMODULATOR

of the gate has a duty cycle that is lower than the previous case, and consequently the average voltage decreases.

- Figure 1e shows the remaining case, in which the instantaneous frequency (ω) has been deviated to greater than the carrier center frequency (ω_0), until the phase shift is < 90 degrees. After integrating, the average voltage is seen to be increased over that in the previous two cases.

We see that as the carrier deviates below and above the carrier center frequency the output voltage swings lower and higher than the nominal value. This provides the frequency-to-voltage conversion required for FM demodulation.

Advantages

Low cost is a major advantage of quadrature demodulators. Specialized integrated circuits are available that have built-in intercarrier detectors, limiters, quadrature demodulators and audio amplifiers.

The output level from a quadrature demodulator is proportional to the "steepness" of the phase slope, or k in Figure 1b. This allows a high output level from the demodulator itself. This high demodulator output level aids in overcoming device noise from the active components. Thus quadrature demodulators usually provide good output signal-to-noise ratio. Passive networks can be built which can provide steep phase slopes at 4.5 MHz, making further downconversion unnecessary. Circuit complexity is consequently reduced even further when compared to most pulse-count demodulators.

Disadvantages

The one significant disadvantage of quadrature demodulators is their somewhat higher distortion when compared to pulse-count demodulators. There are two causes of this distortion. The first is less significant, but fundamental to the operation of the quadrature demodulator. To show this let the phase shift at the shifted multiplier input be represented by the slope-intercept formula for a line

$$\Delta\phi=-k(\omega-\omega_0)+\frac{\pi}{2}$$

$$\Delta\phi=-k\Delta\omega+\frac{\pi}{2} \qquad (1)$$

where
ω_0 is carrier center freq.
ω is instantaneous freq.
$\Delta\Phi$ is phase shift relative to unshifted input
$-k$ is slope (units:seconds)

This is the equation for the plot of Figure 1b.

At the multiplier, for sinusoidal inputs

$$\begin{aligned} Vout&=A\sin(\omega t)\times A\sin(\omega t-k\Delta\omega+\frac{\pi}{2}) \\ &=A^2\sin(\omega t)\times\cos(\omega t-k\Delta\omega) \end{aligned} \qquad (2)$$

Carrying out the multiplication yields a baseband component

$$Vout=-\frac{A^2}{2}\sin(k\Delta\omega) \qquad (3)$$

At this point an approximation is used

$$\sin\theta\cong\theta \qquad \text{for small } \theta$$

to get the ideal transfer function for an FM demodulator.

$$Vout \cong -\frac{A^2}{2}k\Delta\omega \qquad (4)$$

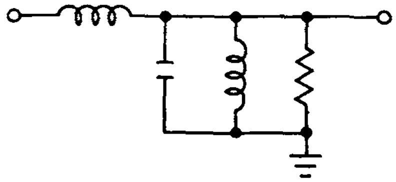
Note that even if k is exactly constant, (i.e. slope is perfectly linear) some distortion is inherent in this technique due to the sine approximation.

But the phase slope k is not constant, as we shall now show. Figure 2a shows a typical single-tuned 90 degree phase shift network. Figure 2b shows the phase response of the network. Note the slight curvature of the phase slope. Group delay is the first derivative of the phase, and as such gives a convenient measure of phase curvature. If the phase slope were perfectly linear, group delay would be a constant. Figure 2c shows the group delay of this network to have a peak-to-peak variation of about 280 nsec.

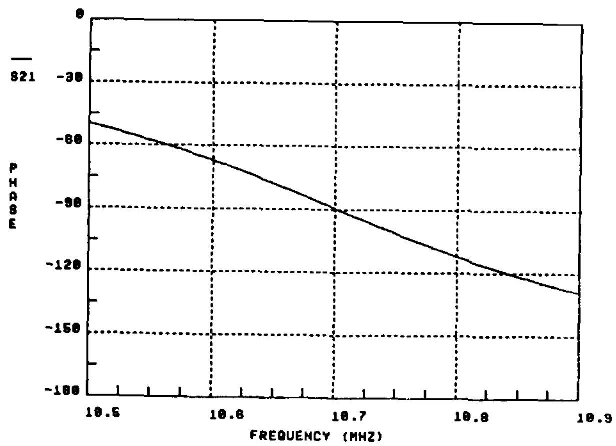
In order to linearize the phase, improve the distortion and increase the output level, a double-tuned network could be used. Figure 3 shows one such network. Note that the phase slope has now increased and become more linear. The group delay has been reduced to about 55 nsec peak-to-peak. Inductive coupling instead of capacitive coupling between the tanks was used to flatten the group delay.

Equation (4) gave the ideal transfer function of a FM demodulator. We would now like to examine the distortion resulting from the phase shift network nonlinearity. An analysis will be done

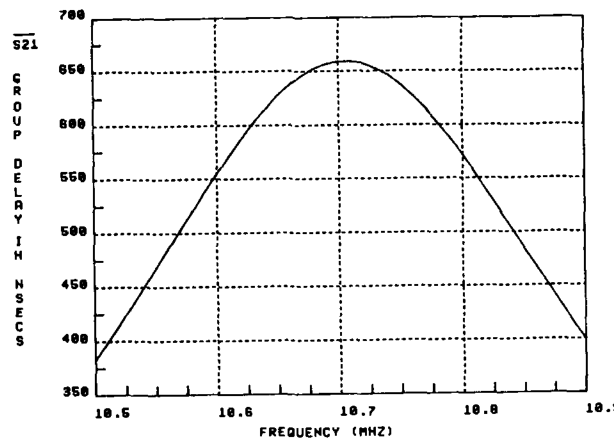
FIGURE 2



a) Single-Tuned Phase Shift Network

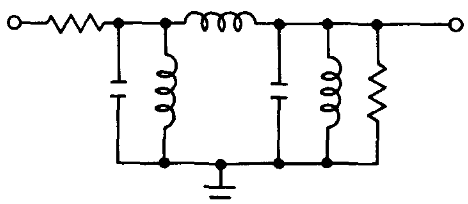


b) Phase Response

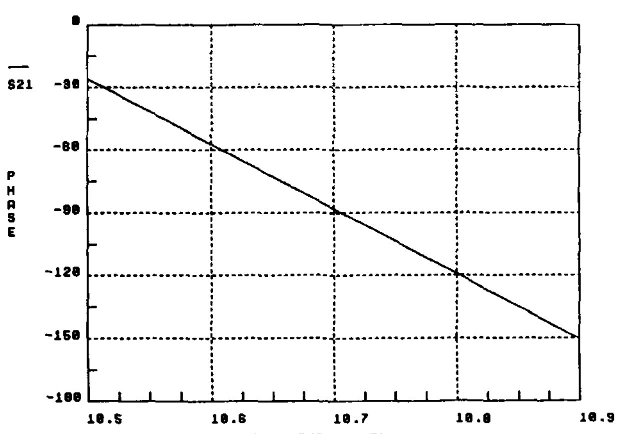


c) Group Delay

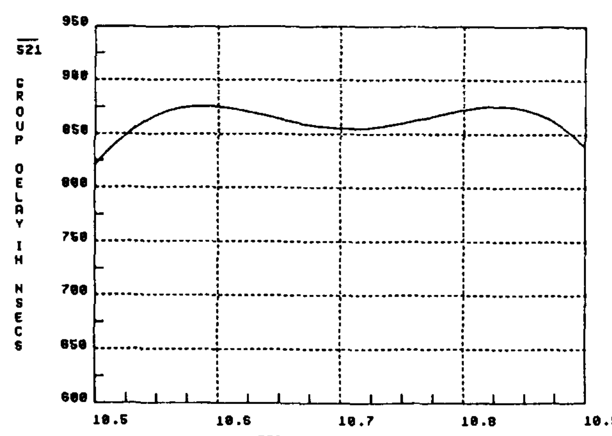
FIGURE 3



a) Double-Tuned Phase Shift Network



b) Phase Response



c) Group Delay

that is very similar to that in reference [1]. In that paper the effect of amplifier nonlinearity was studied in the presence of three carriers. The input was a voltage and the output was a voltage. We will generalize this approach to the case of a nonlinear FM demodulator, where the input is a frequency deviation ($\Delta\omega$) and the output is a voltage.

We can express the transfer function for the quadrature demodulator in a different way.

$$Vout=k_1\Delta\omega+k_2\Delta\omega^2+k_3\Delta\omega^3 \tag{5}$$

where, rather than using a constant k, as we did in equation (4), we use a power series expansion to model the nonlinear phase response.

Now, as an input to this network, let us use an expression for the instantaneous frequency deviation of the carrier as a function of three individual input signals.

$$\Delta\omega=A\cos\omega_a t+B\cos\omega_b t+C\cos\omega_c t \tag{6}$$

where the term in
- A represents a signal in the sum channel,
- B represents the pilot, and
- C, in a simplified way, represents a signal in the difference channel.

This composite input is substituted in the transfer function in (5). The resulting expression is expanded, and if we collect terms by order, we get the results shown in Table 1. This table should look somewhat familiar to CATV engineers accustomed to dealing with distortion products in high level distribution amplifiers.

Note the frequency column in Table 1. This column gives the frequency of the distortion products. The important point to be made here is that due to nonlinearities in the FM demodulator transfer function, signals are produced that fall in channels other

TABLE 1

DISTORTION PRODUCTS

ORDER	FREQUENCY	PEAK AMPLITUDE	DESCRIPTION
1st	fa	k_1A	desired
"	fb	k_1B	"
"	fc	k_1C	"
2nd	dc	$1/2\ k_2(A^2+B^2+C^2)$	dc shift
"	2fa	$1/2\ k_2A^2$	2nd Harmonic
"	2fb	$1/2\ k_2B^2$	"
"	2fc	$1/2\ k_2C^2$	"
"	fa+/-fb	k_2AB	Beat Products
"	fa+/-fc	k_2AC	"
"	fb+/-fc	k_2BC	"
3rd	3fa	$1/4\ k_3A^3$	3rd Harmonic
"	3fb	$1/4\ k_3B^3$	"
"	3fc	$1/4\ k_3C^3$	"
"	2fa+/-fb	$3/4\ k_3A^2B$	Intermodulation
"	2fa+/-fc	$3/4\ k_3A^2C$	"
"	2fb+/-fa	$3/4\ k_3B^2A$	"
"	2fb+/-fc	$3/4\ k_3B^2C$	"
"	2fc+/-fa	$3/4\ k_3C^2A$	"
"	2fc+/-fb	$3/4\ k_3C^2B$	"
"	fa+/-fb+/-fc	$3/2\ k_3ABC$	Triple Beat Products
"	fa	$3/4\ k_3A^3$	Self Compression/Expansion
"	fb	$3/4\ k_3B^3$	"
"	fc	$3/4\ k_3C^3$	"
"	fa	$3/2\ k_3AB^2$	Crossmodulation
"	fa	$3/2\ k_3AC^2$	"
"	fb	$3/2\ k_3BA^2$	"
"	fb	$3/2\ k_3BC^2$	"
"	fc	$3/2\ k_3CA^2$	"
"	fc	$3/2\ k_3CB^2$	"

than those where they originated. Thus pilot and sum frequencies can cause signals in the difference channel. Sum and difference frequencies can cause products in the SAP channel, and many other combinations. Dr. J. James Gibson [2] has compiled a comprehensive table of the possible combinations and the channels that they affect. Suffice it to say that distortion of a composite signal such as BTSC stereo has a more convoluted effect than distortion in single channel audio.

This discussion on distortion due to nonlinearity of the phase shift circuit applies equally to other FM demodulators that depend on a network to establish a linear transfer function. This can be the frequency slope in a discriminator or the frequency-vs-control voltage function in a phase-locked-loop FM demodulator.

The availability of encompassing "jungle" IC's with most of the components necessary for a full demodulator makes the quadrature demodulator difficult to ignore for consumer applications, despite the somewhat higher distortion.

PULSE-COUNT DEMODULATORS

Figure 4a shows a block diagram of a pulse-count demodulator. The term pulse-count is probably a misnomer, because no counting actually occurs. The name "pulse-averaging demodulator" is sometimes used and is more descriptive of the operation of the circuit. A one-shot is triggered on every rising edge of the limited FM carrier. The output of the one-shot is a pulse that lasts for one half-cycle of the unmodulated carrier. To illustrate the operation we again consider three separate cases.

- Figure 4b shows the case in which the instantaneous frequency (ω) is at the carrier center frequency (ω_0). The output of the one-shot is a pulse-train of 50% duty cycle. After integrating we find that the average voltage of the pulse-train is halfway between the top and the bottom.

- Figure 4c shows the case in which the instantaneous frequency (ω) has been deviated to less than the carrier center frequency (ω_0). The pulses out of the one-shot are the same width as before, but now the time between them has increased. After integrating, we find the average voltage to be less than in the previous case.

- Figure 4d shows the remaining case, in which the instantaneous frequency (ω) has been deviated to greater than the carrier center frequency (ω_0). Now after integrating the average voltage is seen to be increased over that in the previous two cases.

Advantages

Again we see that as the carrier deviates below and above the carrier center frequency the output voltage swings lower and higher than the nominal value, thus providing the required frequency-to-voltage conversion for FM demodulation. In theory significant distortion does not occur until the carrier is deviated to twice the center frequency. Effectively, all the distortion in a carefully designed demodulator using a pulse-count demodulator is due to group delay in the preceding filters. This makes the pulse-count demodulator an excellent choice for applications involving high percent deviations or in very low distortion applications.

Disadvantages

Unfortunately, even with the relatively wide deviations of BTSC stereo, the percent deviation at 4.5 MHz is somewhat low at

100 x 73 kHz/4.5 MHz = 1.6%.

This normally results in a low output level from the demodulator. More baseband gain is required, and whatever noise accompanies the signal is also amplified.

The usual solution (not the only solution) to this problem is to further downconvert to a lower IF frequency, often about 1 MHz. This increases the percent deviation to

100 x 73 kHz/1 MHz = 7.3%

which is somewhat easier to deal with.

This solution is not without significant penalty, however. Circuit cost and complexity is increased by the requirements for another mixer, oscillator and IF bandpass filter. A less obvious problem is that the baseband filter now has to reject the much lower IF at 1 MHz while passing the composite BTSC waveform out to 110 kHz. Maintaining the recommended flatness of +/- .05 dB for monitoring and measurement equipment through such a filter becomes a more difficult task than with a final IF at 4.5 MHz.

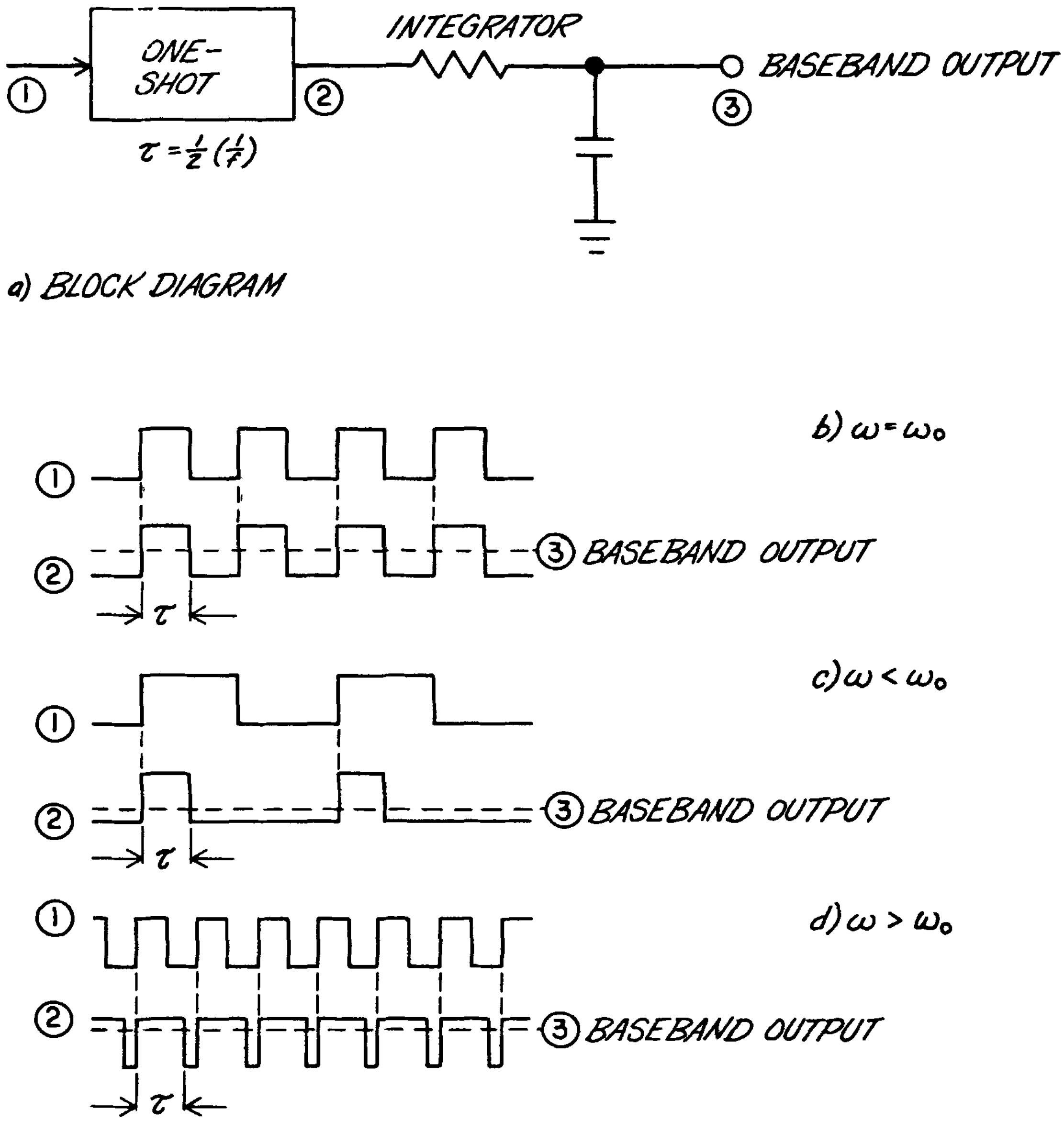


FIGURE 4. PULSE-COUNT DEMODULATOR

The very low distortion but higher cost and complexity of the pulse-count demodulator makes it better suited for applications in professional monitoring and measurement, as opposed to consumer equipment.

FURTHER CONSIDERATIONS

Although noise is always an important consideration, two factors combine to make it less significant in BTSC stereo than one might expect. The carrier to noise ratio required for the video usually puts the audio well above FM threshold. Also, the dbx[1] noise reduction used in the difference channel effectively masks an otherwise objectionable noise floor in marginal reception conditions.

Buzz is normally a much more significant concern in BTSC stereo than noise. Sources of buzz in television audio have been covered in the literature [2],[3]. This paper has concentrated on the FM demodulator itself and not on the associated circuitry and receiver architecture. It is mostly up to the associated circuitry and system and architecture choices to reject buzz and phase noise.

But it is also important that the FM demodulator not contribute to the buzz problem. Good AM rejection in the limiter and demodulator is important here, particularly in the presence of audio carrier tag and timing pulses often used in cable security systems. The pulse-count demodulator, being essentially a digital circuit, has inherently good AM rejection. Phase-locked-loop demodulators can also provide good protection against AM.

The importance of maintaining good frequency response flatness and good phase linearity in the demodulator and subsequent circuits cannot be overstated. For monitoring and measurement applications a flatness of +/- .05 dB and phase deviation < +/- .5 degree from linear is required to maintain sufficient stereo separation in the system [4]. In some cases the internal audio amplifier in an IC may limit the achievable response.

1. dbx is a registered trademark of dbx inc.

CONCLUSION

Quadrature demodulators and pulse-count demodulators are commonly used to demodulate BTSC stereo carriers. These two types of demodulators were described. Waveform plots were used to illustrate their operation. The effect of different performance parameters on BTSC stereo was discussed.

Low cost, good noise performance and integrated circuit availability combine to make the quadrature demodulator a good choice for consumer products, despite its somewhat higher distortion. For the ultimate in low distortion at the price of increased circuit complexity and cost, the pulse-count demodulator is difficult to equal. For this reason pulse-count demodulators are found in professional monitoring and measurement equipment.

REFERENCES

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[3] Robbins, Clyde, "BTSC: The Stereo For Cable", 1986 NCTA Technical Papers.

[4] "BTSC System Recommended Practices", EIA Television Systems Bulletin No. 5.