Frequency Discriminator

1) Background and History

Frequency discriminators have already been well known for a long time. At first they were used as part of automatic frequency control systems in radio receivers ([1], [2]). As early as in the year 1932 Prof. Edwin H. Armstrong proposed the use of the broadband frequency modulation as a means againt atmospheric noise. By the end of the year 1936 the Federal Communications Commission (FCC) accorded him a licence for five experimental FM channels and it became soon clear that frequency discriminators are of paramount importance in the demodulation of frequency modulated signals. This pourpose has evertime been the predominent application of these discriminators. Several studies and analyses have revealed the properties of these circuits, especially in the broadcasting and television related applications. The demodulation linearity is the most important parameter in this area and it has been investigated in several studies (e.g. [3], [13], [16], [17]). Applications in other areas do not often require a highly linear demodulation, e.g. in the initial application related to automatic frequency control systems.

Previously, frequency discriminators were simply designed using passive components only ([1], [2], [4], [5], [10]). Later, circuits were designed with active components too, the passive ones being often used as some sort of phase rotating circuit part. The first circuits with active components were usually built around a special tube. The best known tube for such applications is the 6BN6 ([6], [7], [8], [11], [12], [13], [18]). Some other tubes were developed, based on the same principles or as an extension of them, e.g. the EQ80 and the 6DT6 ([13], [15]). The synchro-detectors are a further group of frequency discriminators using active components. Initially current tubes were used but special ones were then developed for this application, the most popular one being probably the FM1000 from Philco. Using today's terminology, synchro-detectors may be looked upon as an especially compact and elegant form of Phase Locked Loops (PLL). This compact design was necessary because electronic tubes were the only available active components at that time. Synchro-detectors could only be accepted for practical use in this compact form, nevertheless they were rather uncommon.

In the beginning of the semiconductor era, these principles were first adapted to the requirements of the new technology. Later on, there was an important adaptation to the semiconductor technology, especially the LSI. Further circuits based on different principles were of course considered as well, but they hardly raised any interest. (e.g. [14]).

The basic idea behind the discriminator circuits using only passive components is the following: the input signal is fed through two different frequency selective channels, they are then rectified and the output signal of both rectifiers is added with inverse polarity, giving the output signal of the discriminator. This basic form is found in the Travis discriminator ([1]) but the Ratio-Detector ([4]) as well as the Foster-Seeley discriminator ([2]) use a very similar base as G.G. Johnstone has proved ([13]). It is interesting to note here that bandpass filters of the second order (or electrically equivalent circuits) are nearly always used as frequency selective element in the two frequency selective channels. Rarely, inductively coupled bandpass filters are used, i.e. bandpass filters of the fourth order. Only recently circuits using different frequency selective elements have been used, e.g. in the MR-77 discriminator. The frequency selective elements of this discriminator are a $\lambda/8$ coaxial line with an open end line in the first channel and a shorted end line in the second channel. The behavior of a coaxial line and a lumped constants circuit is not the same over a large frequency range, therefore, the behavior the the MR-77 discriminator cannot simply be compared to discriminators of the Travis type. The designers of the MR-77 discriminator claimed to achieve a better linearity. It is interesting to note, that the selective elements used here have zeros in the transfer functions (other that at $s = 0$ and $s = \infty$) contrarly to the selective elements used in the circuits first cited. These zeroes are clearly located outside the useful frequency range, their influence on the discriminator behavior is limited.

2) The new circuit

The new circuit adheres to the tradition of circuits using only passive components. This view is maintained even if the filters are built using active filter circuits because the resulting behavior is only a simulation of a passive filter circuit. The preference given to active filters can only result from practical considerations. On the other hand, the new circuit differs from traditional ones because the transfer function of the selective circuits used in the frequency selective channels contains zeroes in the useful frequency band. These zeroes have an important influence on behavior.

2.1) Principles of the circuit

The selective circuits used in the selective channels of the common discriminators are nearly always bandpass filters. In contrast, the new circuit uses a bandpass circuit with highpass behavior in the first channel and a bandpass filter with lowpass behavior in the second channel. Usually second order filters, each with a zeroes pair on the s-axis, are used. Both filters have the pole at the same location on the transfer function but the zeroes at different locations.

2.2) Behavior

The magnitude vs. frequency response of a filter depends on the location of the poles and zeroes of its transfer function. The phase vs. frequency response of a filter depends on the location of the poles and zeroes of its transfer function, unless the zeroes are located exactly on the s-axis. The new circuit profits from these facts. Both channels show the same phase vs. frequency behavior but a different magnitude vs. frequency behavior. However, the sign of the magnitude can change what is equivalent to a phase change of 180 degrees.

A good base for a practical circuit is the three amplifier biquad circuit ([19], [20]). This circuit is common to the two channels and creates the common pole pair. The same circuit used for both channels ensures that the pole of both channel is located exactly at the same place. Further, a summing amplifier specific to each channel is used in order to add the zeroes pair to the transfer function.

2.3) Properties

The magnitude vs. frequency behavior of the new discriminator shows some analogies to the common discriminator circuits but the linearity is limited. This circuit is not recommended for the demodulation of signals commonly encountred in the broadcasting and television area. The limited linearity is not a problem when the circuit is used to demodu-

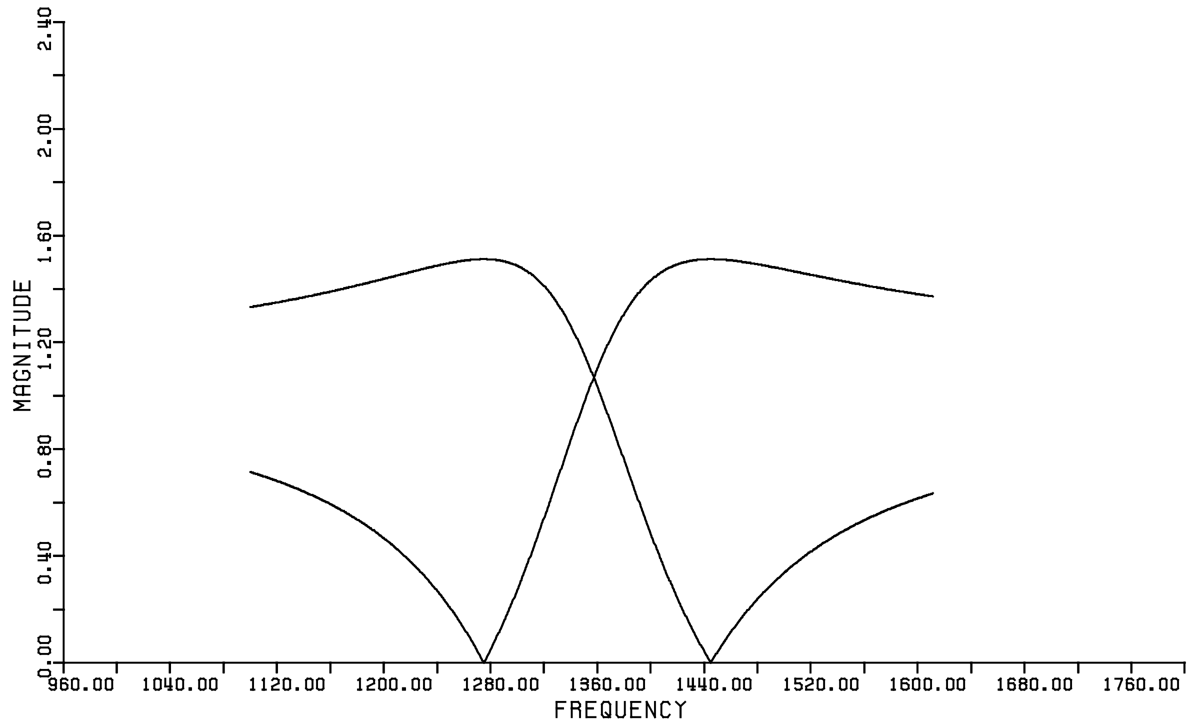

Fig. 1 Magnitude response of both channels

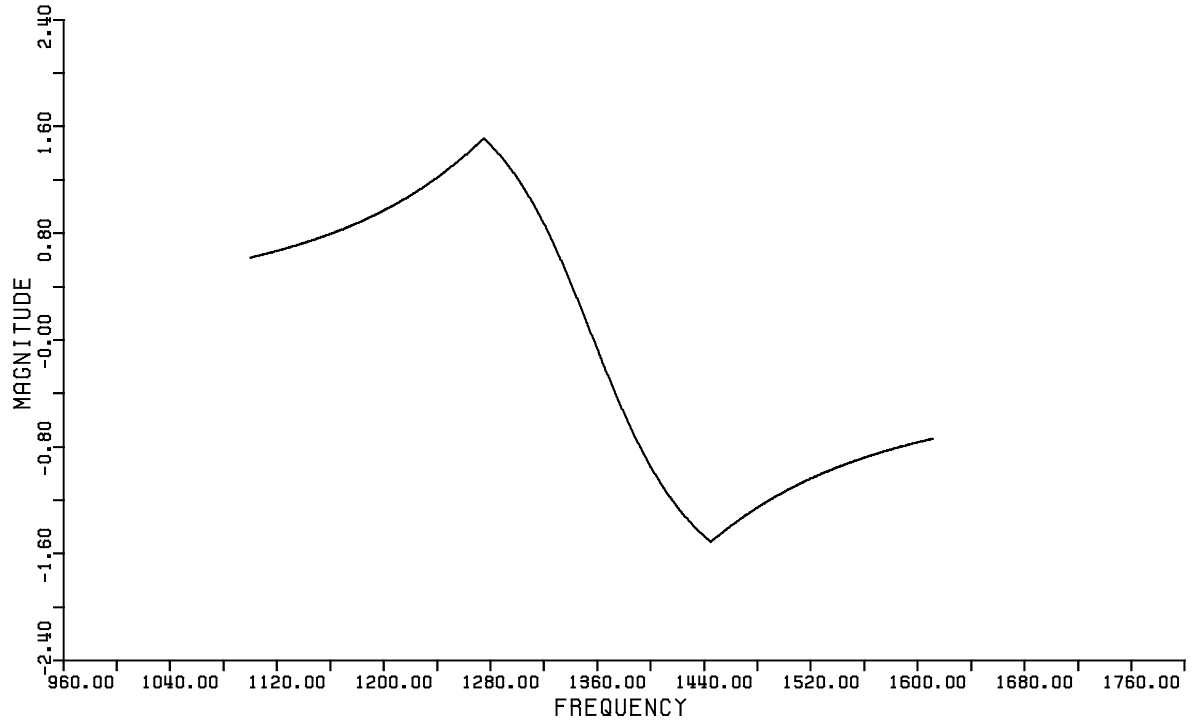

Fig. 2 Difference of magnitude of both channels

late digital signals. This circuit is a good choice for this purpose, the overshoot behavior is especially interesting.

A special property of this circuit is that a very simple but very effective tuning indicator can be added to it. If the signals found at the output of each filter are amplified appropriately and applied to the X and Y deflection systems of an CRT, the screen shows a straight line with the angle dependent on the frequency and the length dependent on the magnitude of the signal at the input of the discriminator circuit. This one can be designed in such a manner that the length of the line on the CRT is nearly constant over the useful frequency range. When the circuit is used to demodulate FSK signals, a good choice is to assign the vertical line position to the one digital polarity of the signal and the horizontal position to the other one, achieved by locating the zeroes pairs at the frequencies corresponding to the two polarities of the input signal. The frequency corresponding to the common pole is usually located at the geometric mean of the frequency corresponding to the zeroes pairs.

3) Design example

In order to emphasize the exposed principle, an design example is given here. The space frequency is 1275 Hz, the mark frequency is 1445 Hz, therefore, the nominal shift is 170 Hz.

Fig. 1 shows the magnitude vs. frequency response of both selective channels considered separately, in contrast, Fig. 2 shows the difference of the magnitude of both channels, i.e. the output signal of the discriminator. The pole frequency is the geometric mean of the zero frequencies, the Q value is 8.016 for both channels and the k ratio between the two channels is 1.1333. Fig. 3 shows an actual photograph of a CRT encountering a signal with a correct shift, by contrast, Fig. 4 shows a shift greater than the expected one used in this design example. Fig. 6 shows the position of the trace on the CRT depending on the frequency difference relatively to the mark frequency.

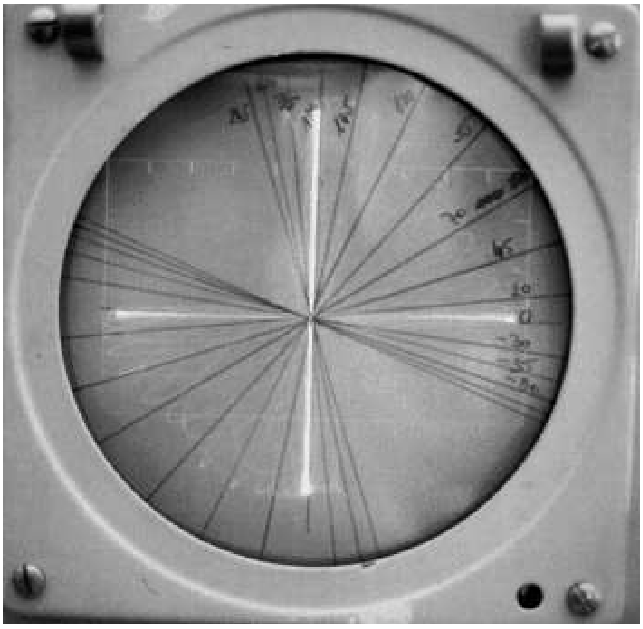

Fig. 3 CRT trace for a correct shift

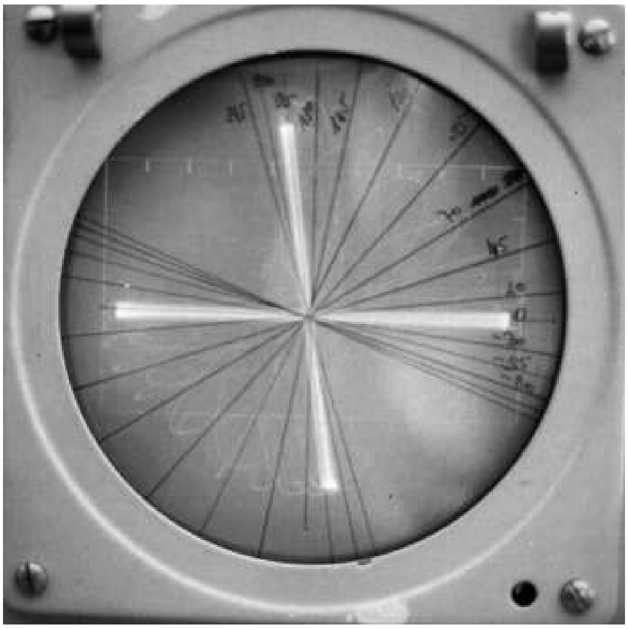

Fig. 4 CRT trace for a shift greater than expected

Now, we will examine an example of a practical realization of such a circuit, refering to Fig. 5 (the rectifier circuit is not showed). The core of this circuit is the classical 3 amplifier biquad circuit common to both filter channels. This ensures exactly the same pole for both channels. We recognize the integrator, the leaky integrator and the inverter stage, each one built using an operation amplifier, U2, U1 and U3 respectivelly. For a

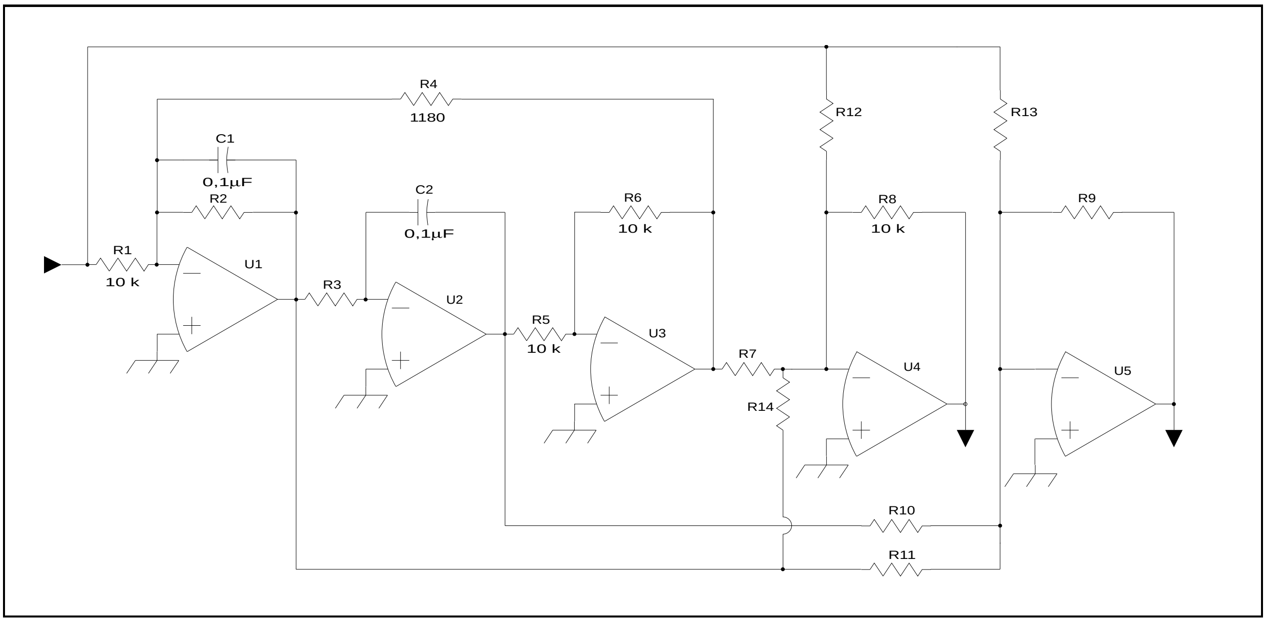

Fig. 5 The example circuit

good reference to the 3 amplifier biquad circuit, see [21] and [22]. The zero of the transfer function is introduced using a summing amplifier specific to each channel, namely U4 (having the notch frequency at 1275 Hz) and U5 (having the notch frequency at 1445 Hz).

The pole frequency is the geometric mean of the space and mark frequencies:

$$\omega_{pole}=\sqrt{\omega_{space}\cdot\omega_{mark}}$$

The zeroes on the imaginary axis are on the space and mark frequencies respectively.

The pole Q is chosen as:

$$Q_{pole}=\sqrt{\frac{\omega_{\max}^4-\omega_{zero}^4}{2\left(\omega_{\max}^4-\omega_{zero}^4-2\cdot\omega_{zero}\cdot\omega_{\max}^3+2\cdot\omega_{zero}^3\cdot\omega_{\max}\right)}}$$

ω_{max} being the frequency at which the maximum of magnitude of the output signal occurs, ω_{zero} being the frequency at which the zero of magnitude of the output signal occurs. These frequencies are the mark and space frequencies, exchanged in the case of the one and the other channel filter.

The constant magnitude multiplicator ratio of the channel with the highest pass frequency in respect to the other channel is:

$$\frac{f_{low}}{f_{high}}=\frac{\omega_{low}}{\omega_{high}}$$

R2 ajusts Q_p, R3 ajusts ω_p, R7 and R10 ajust ω_z, R11 and R14 adjust the Q_z, R12 and R13 adjust the gain, i.e. the constant magnitude multiplicator too. Note that all adjustments related to the pole are common for both channels, in contrast the zero related adjustments are separate.

4) References

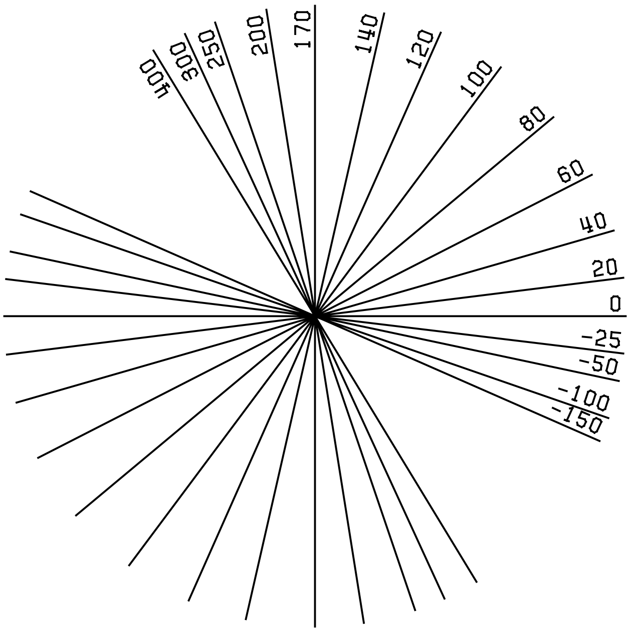

Fig. 6 Trace location on the CRT depending on the frequency relatively to the mark frequency

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