United States Patent [19]

Gebel et al.

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[45] **Feb. 12, 1974**

[54] **CONTROLLABLE EDGE SHARPENING SYSTEM FOR TIME SEQUENTIAL SIGNALS**

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[73] Assignee: **The United States of America as represented by the Secretary of the Air Force,** Washington, D.C.

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[21] Appl. No.: **247,775**

[52] **U.S. Cl.** **328/164,** 307/263, 307/268, 328/127

[51] **Int. Cl.** **H03k 5/12,** H04b 1/12

[58] **Field of Search** 307/230, 263, 268; 328/164, 328/127

[56] **References Cited**

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Primary Examiner—John Zazworsky

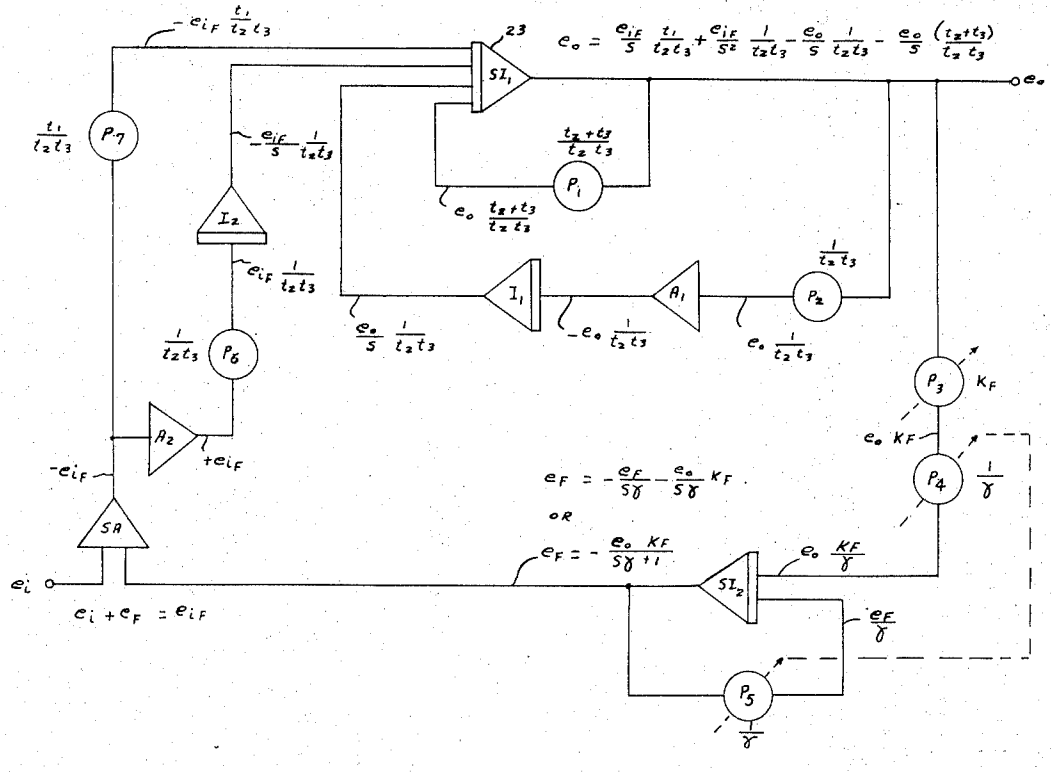
[57] **ABSTRACT**

A time sequential signal having deficient leading and trailing edge characteristics is modified by a system having a third order network with a transfer function represented in the Laplace domain by

$$F_R(s)=\frac{e_o}{e_i}=\frac{\dfrac{(1+s\tau_1)}{(1+s\tau_2)(1+s\tau_3)}}{1+K_F\dfrac{(1+s\tau_1)}{(1+s\tau_2)(1+s\tau_3)(1+s\gamma)}}$$

where s is the Laplace variable in sec^{-1}, τ_1, τ_2, τ_3, γ are time constants in seconds, and K_F is an attenuation factor, with e_o being the output and e_i the input signal. This system provides an improved signal having leading and trailing edge characteristics suitable for utilization.

4 Claims, 22 Drawing Figures



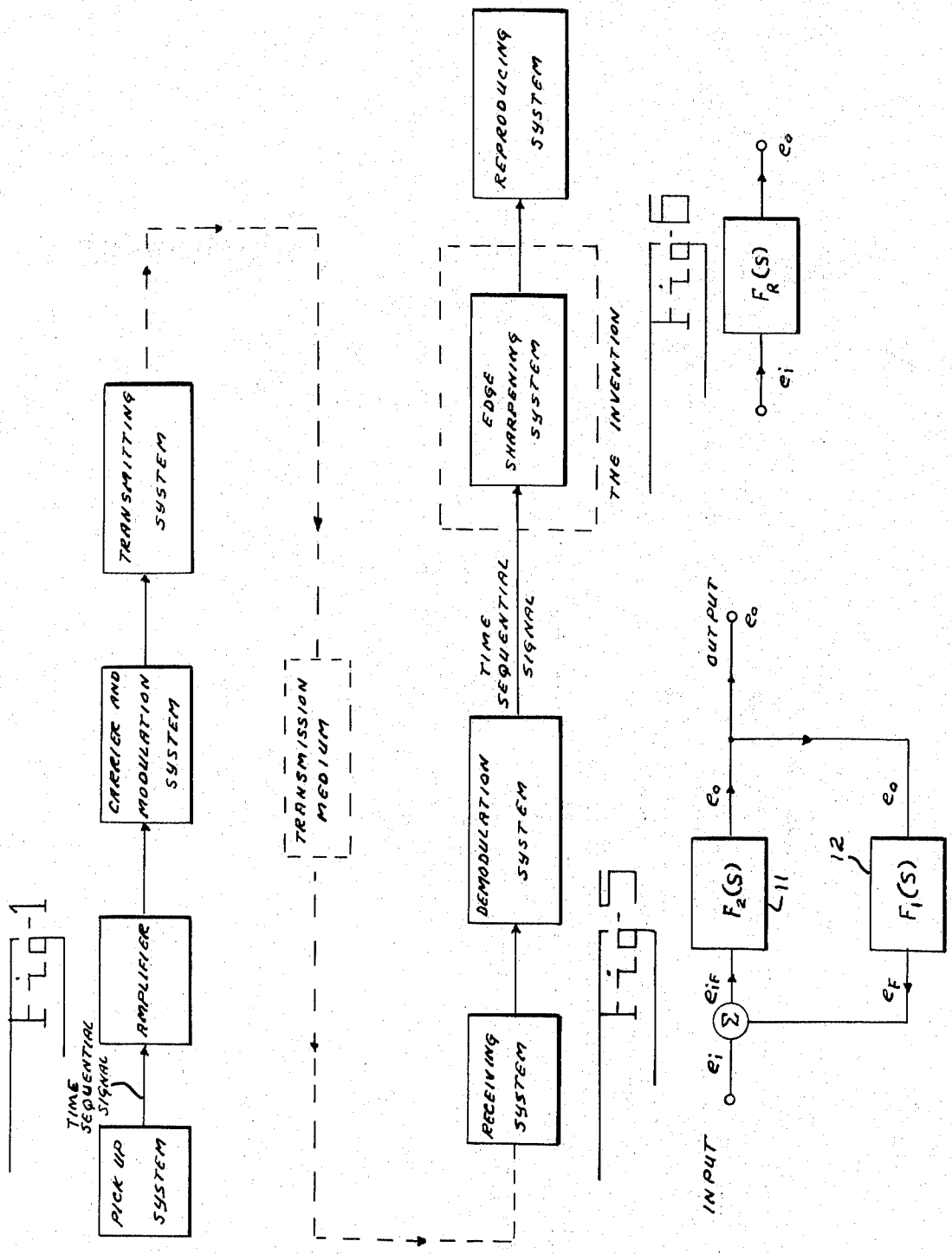


Fig-1

Fig-5

Fig-6

Fig-4

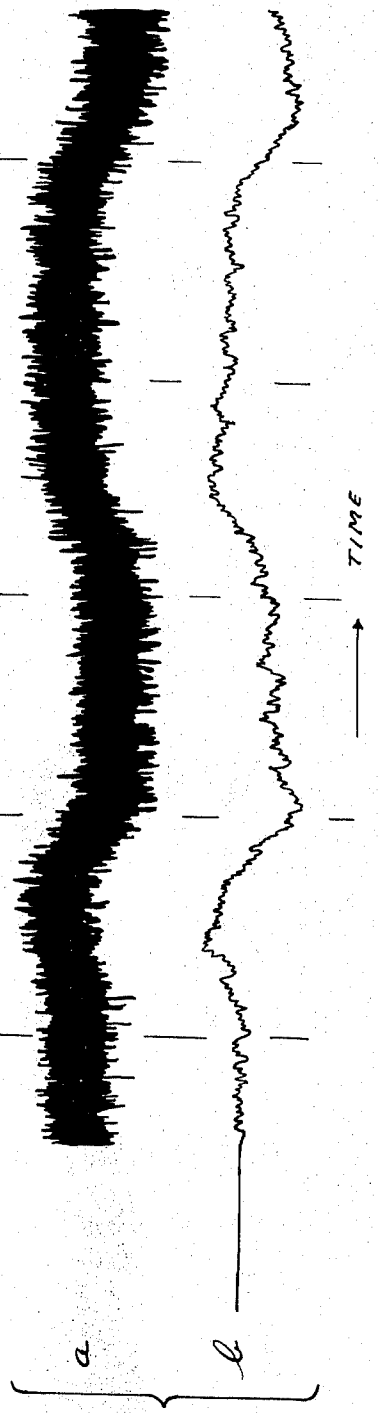


Fig-3

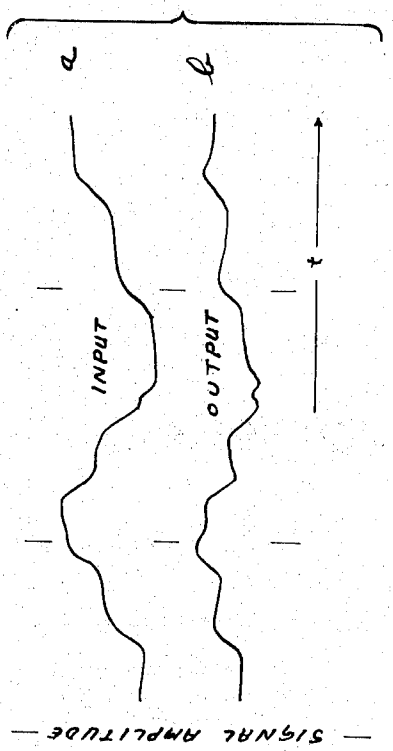
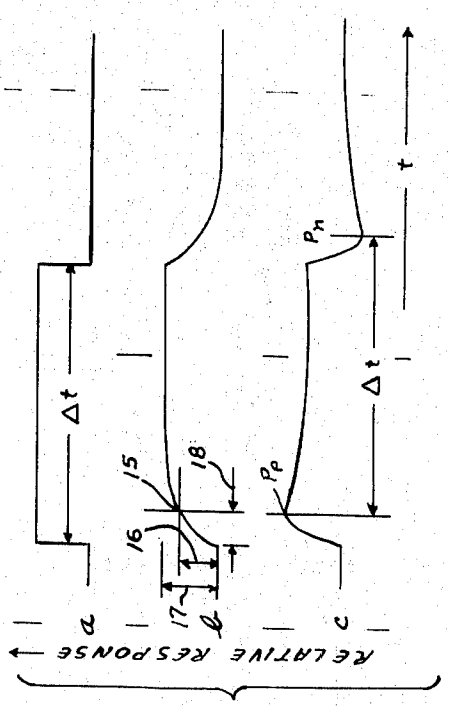


Fig-2



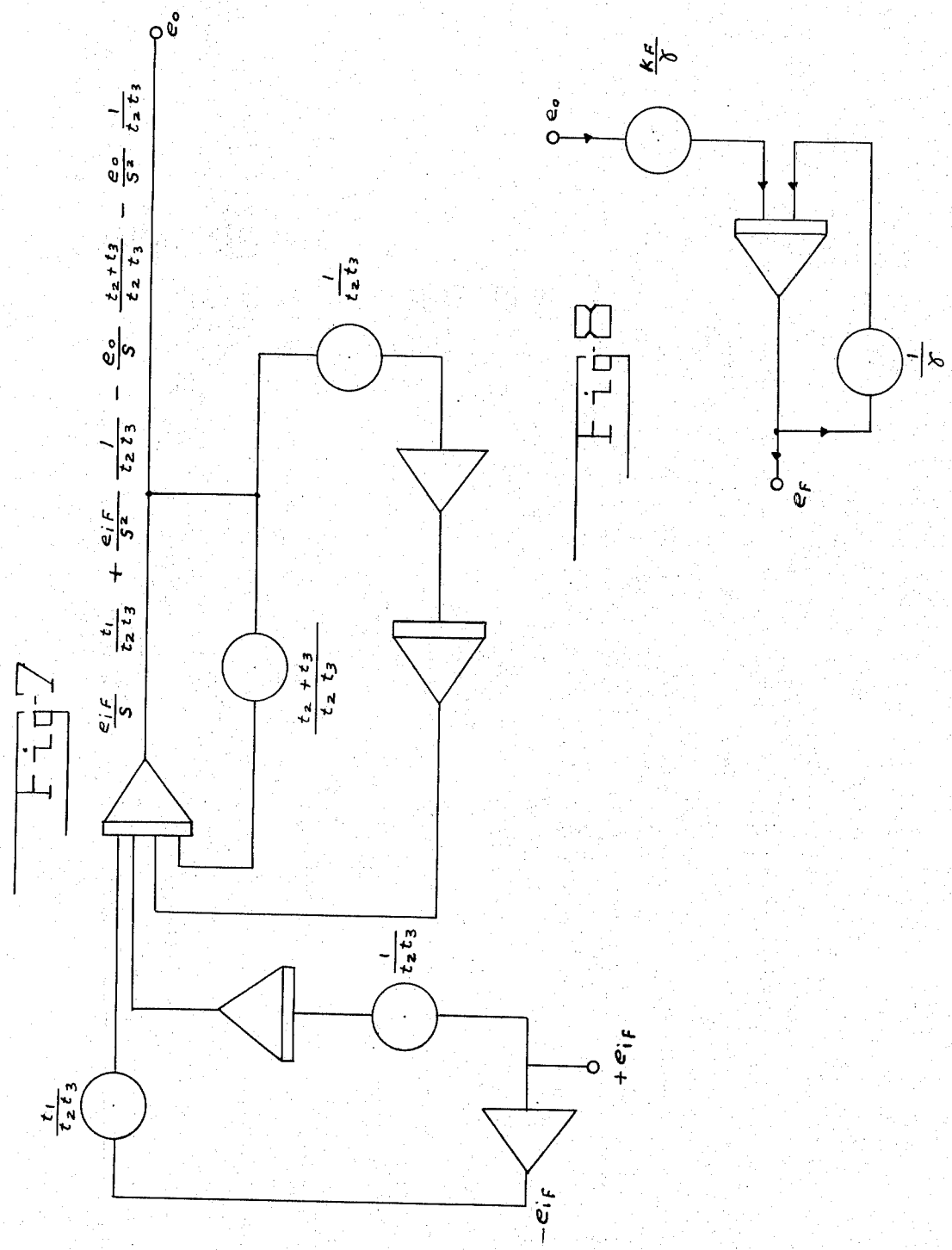

e_o
$\frac{e_{iF}}{S}$ $\frac{t_1}{t_2 t_3}$ + $\frac{e_{iF}}{S^2}$ $\frac{1}{t_2 t_3}$ - $\frac{e_o}{S}$ $\frac{t_2+t_3}{t_2 t_3}$ - $\frac{e_o}{S^2}$ $\frac{1}{t_2 t_3}$
$\frac{1}{t_2 t_3}$
$\frac{t_2+t_3}{t_2 t_3}$
$\frac{t_1}{t_2 t_3}$
$\frac{1}{t_2 t_3}$
$+e_{iF}$
$-e_{iF}$
Fig. 7
Fig. 8
e_o
$\frac{K_F}{\delta}$
$\frac{1}{\delta}$
e_F

Fig-9

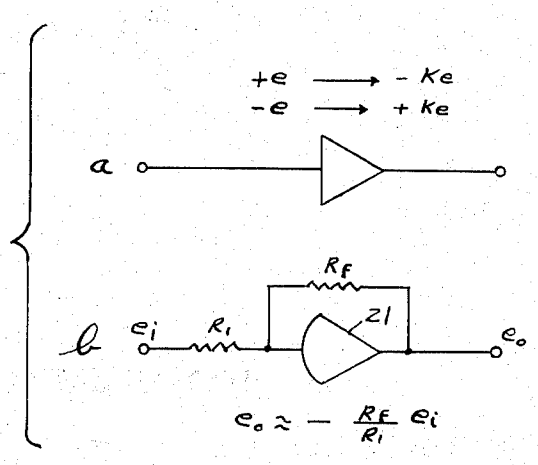


Fig-10

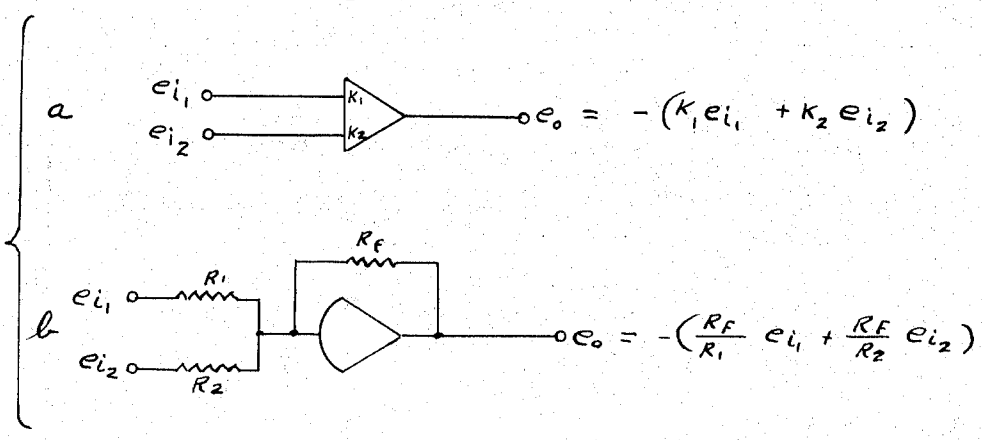


Fig-11

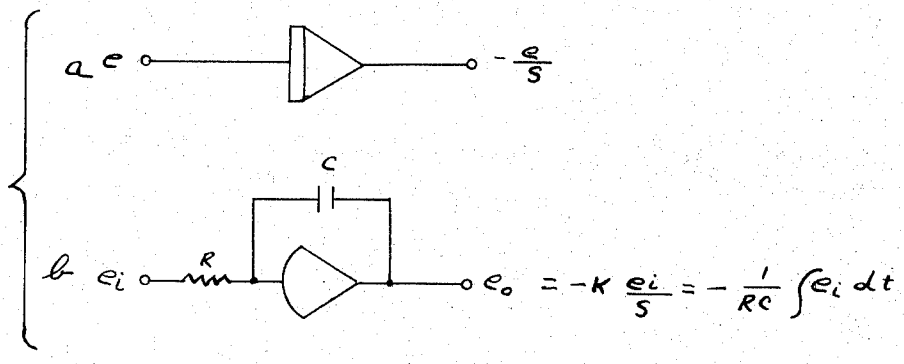


Fig-12

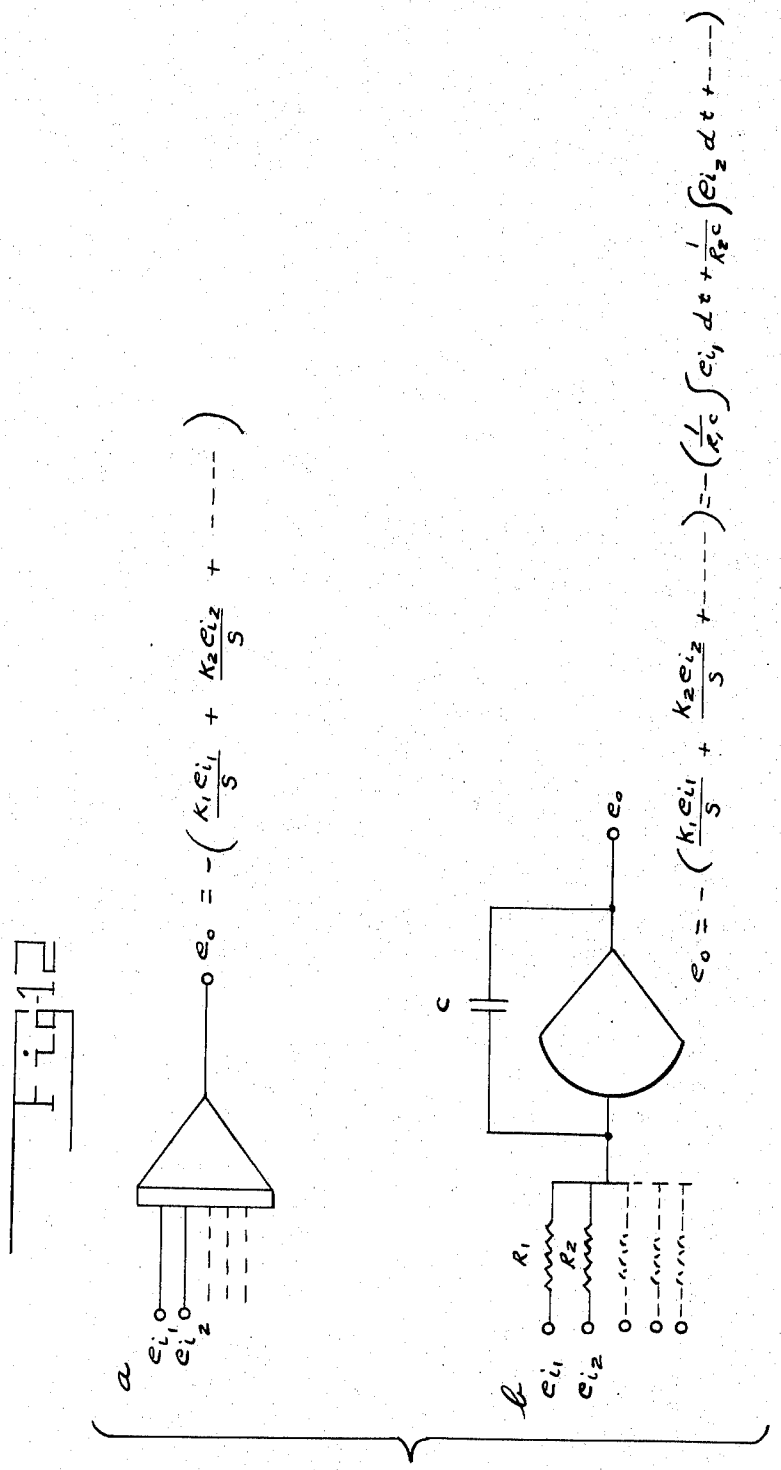
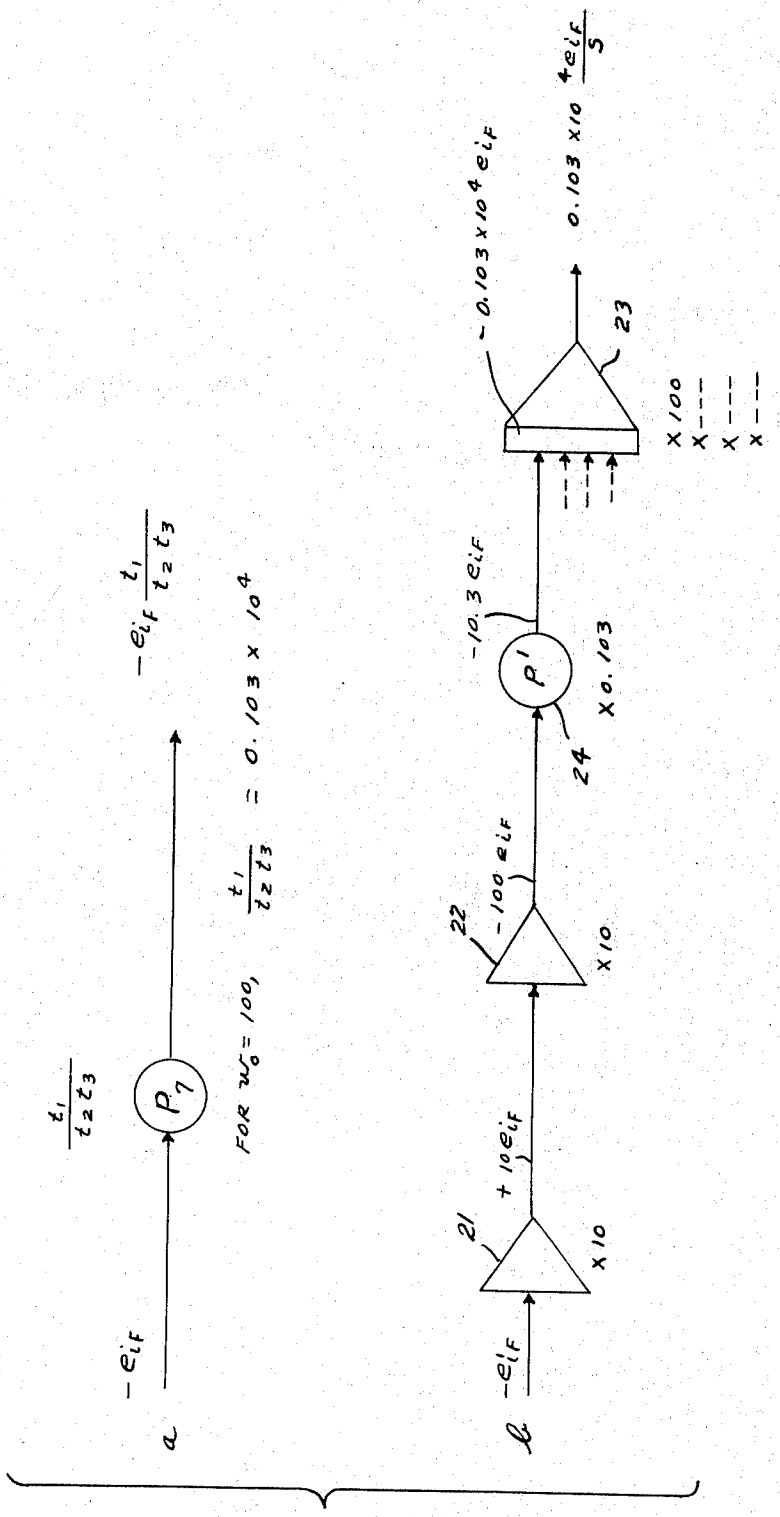

a
e_{i_1}
e_{i_2}
$e_o = -\left(\frac{K_1 e_{i_1}}{S} + \frac{K_2 e_{i_2}}{S} + \cdots\right)$
b
R_1
R_2
C
e_o
$e_o = -\left(\frac{K_1 e_{i_1}}{S} + \frac{K_2 e_{i_2}}{S} + \cdots\right) = -\left(\frac{1}{K_1 C}\int e_{i_1} dt + \frac{1}{K_2 C}\int e_{i_2} dt + \cdots\right)$

Fig-13


$-e_{iF}$
a
$\frac{t_1}{t_2 t_3}$
P_7
$-e_{iF}\frac{t_1}{t_2 t_3}$
FOR $\omega_0 = 100$, $\frac{t_1}{t_2 t_3} = 0.103 \times 10^4$
$-e_{iF}'$
b
21
$+10 e_{iF}$
X 10
22
$-100 e_{iF}$
X 10
24
P_1
$-10.3 e_{iF}$
X 0.103
23
$-0.103 \times 10^4 e_{iF}$
$0.103 \times 10 \frac{4 e_{iF}}{S}$
X 100
X
X
X

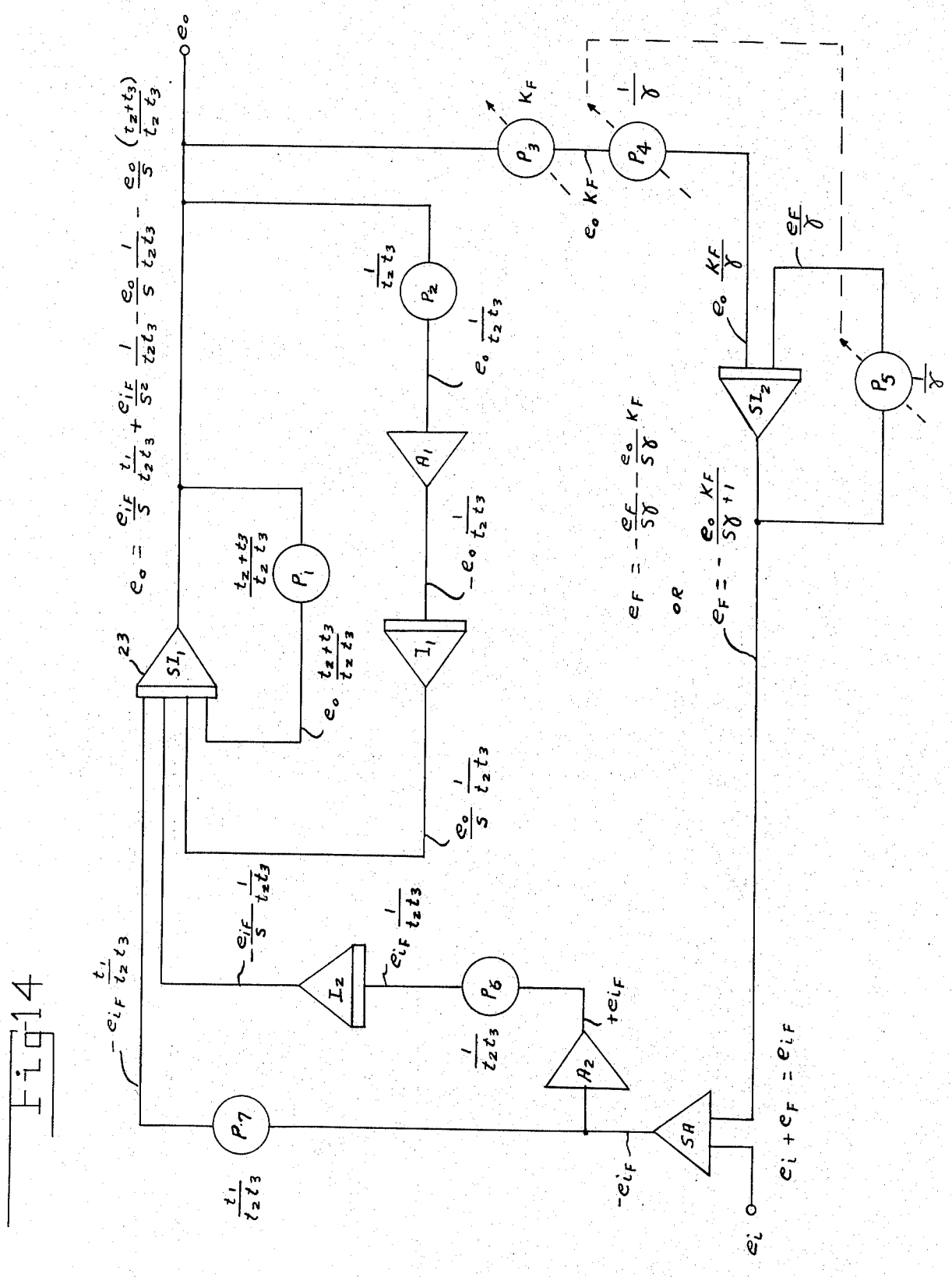

e_o
$e_o = \frac{e_{iF}}{S}\frac{t_1}{t_2 t_3} + \frac{e_{iF}}{S^2}\frac{1}{t_2 t_3} - \frac{e_o}{S}\frac{1}{t_2 t_3} - \frac{e_o}{S}\left(\frac{t_2+t_3}{t_2 t_3}\right)$
P_3
K_F
P_4
$\frac{1}{\gamma}$
$e_o K_F$
P_2
$\frac{1}{t_2 t_3}$
$e_o \frac{1}{t_2 t_3}$
A_1
$-e_o \frac{1}{t_2 t_3}$
P_1
$\frac{t_2+t_3}{t_2 t_3}$
$e_o \frac{t_2+t_3}{t_2 t_3}$
23
SI_1
I_1
$\frac{e_o}{S}\frac{1}{t_2 t_3}$
$e_o \frac{K_F}{\gamma}$
$\frac{e_F}{\gamma}$
SI_2
P_5
$\frac{1}{\gamma}$
$e_F = -\frac{e_F}{S\gamma} - \frac{e_o}{S\gamma}K_F$
OR
$e_F = -\frac{e_o K_F}{S\gamma + 1}$
$-\frac{e_{iF}}{S}\frac{1}{t_2 t_3}$
I_2
$e_{iF}\frac{1}{t_2 t_3}$
P_6
$+e_{iF}$
$-e_{iF}\frac{t_1}{t_2 t_3}$
A_2
$\frac{1}{t_2 t_3}$
P_7
$\frac{t_1}{t_2 t_3}$
$-e_{iF}$
SA
$e_i + e_F = e_{iF}$
e_i

Fig 14

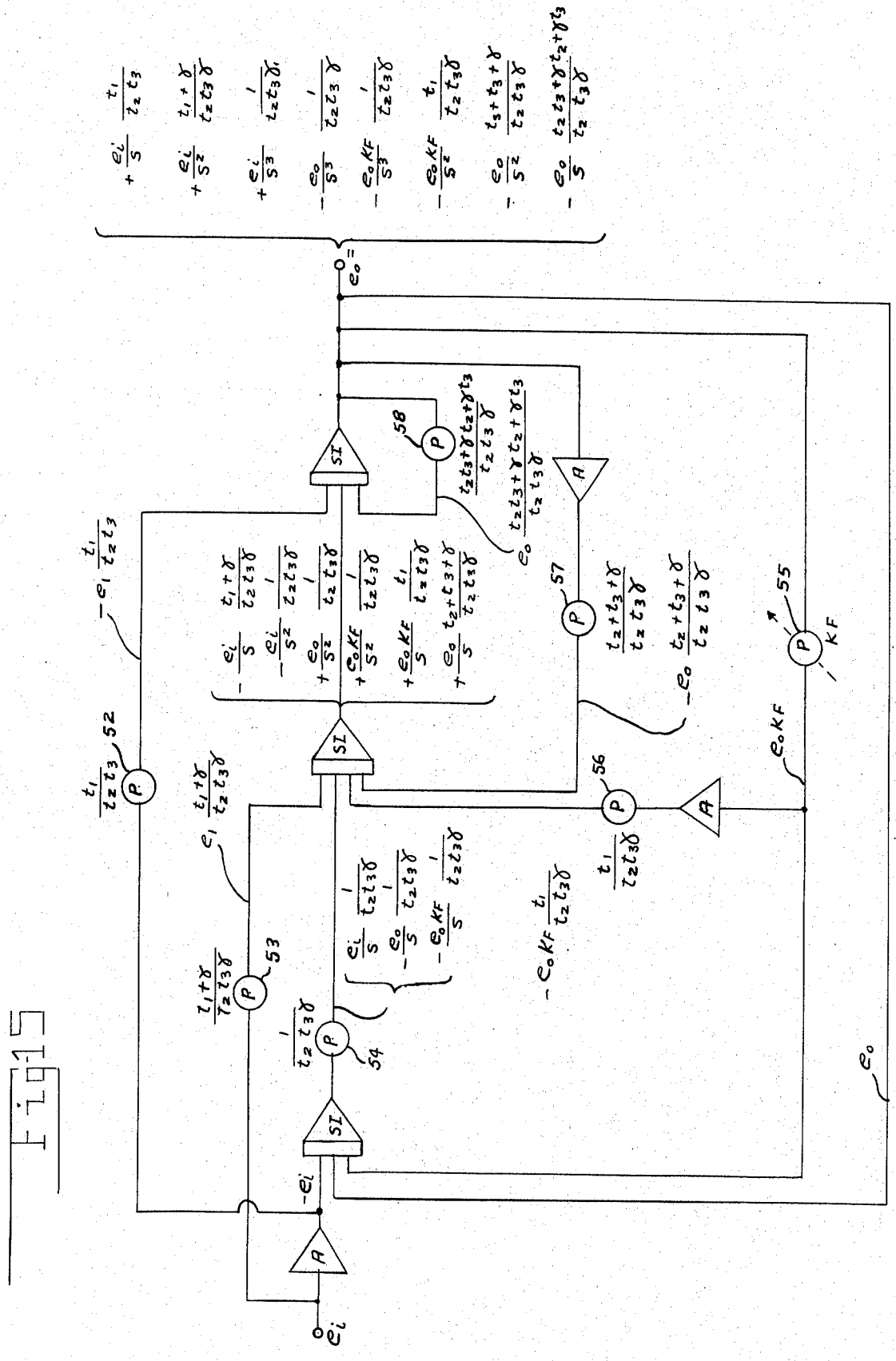


Fig. 15

Fig 16

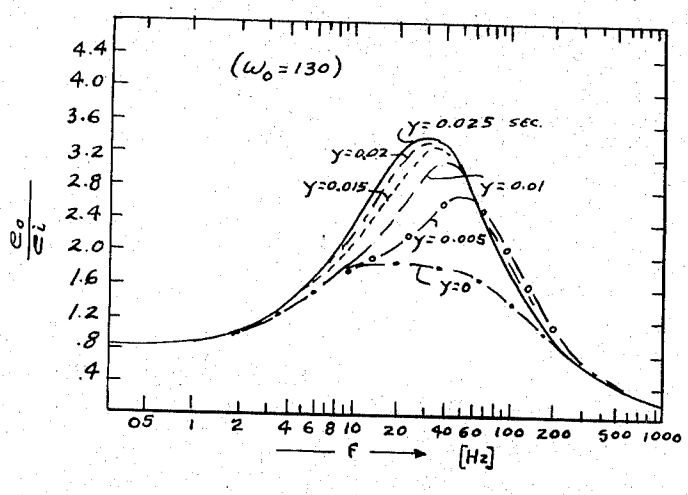


Fig 17

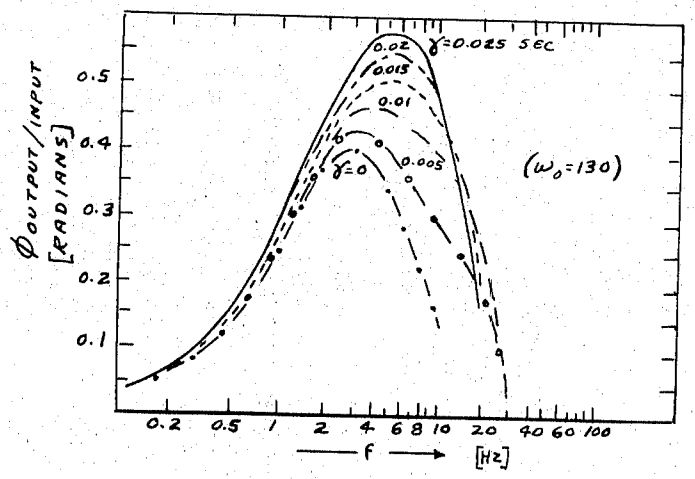


Fig 18

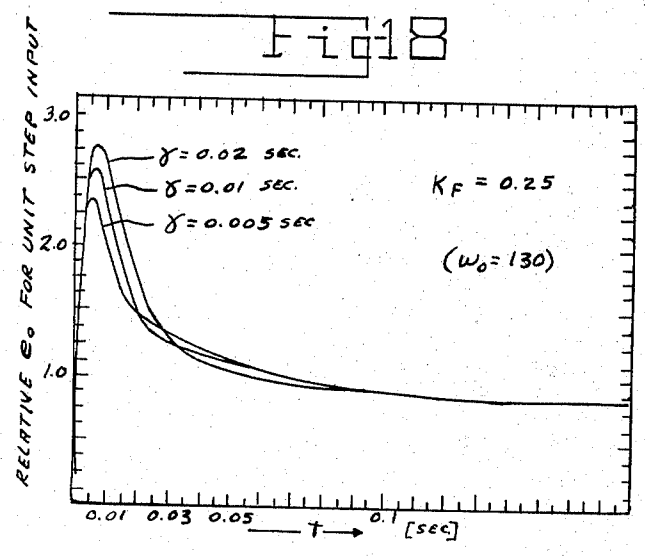


Fig-19

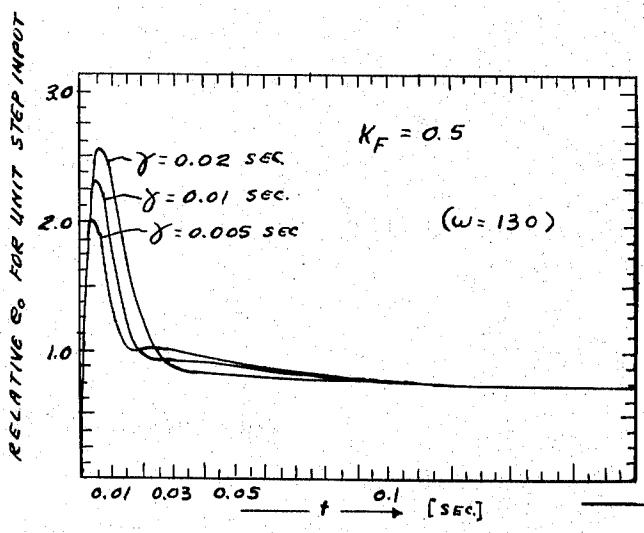


Fig-20

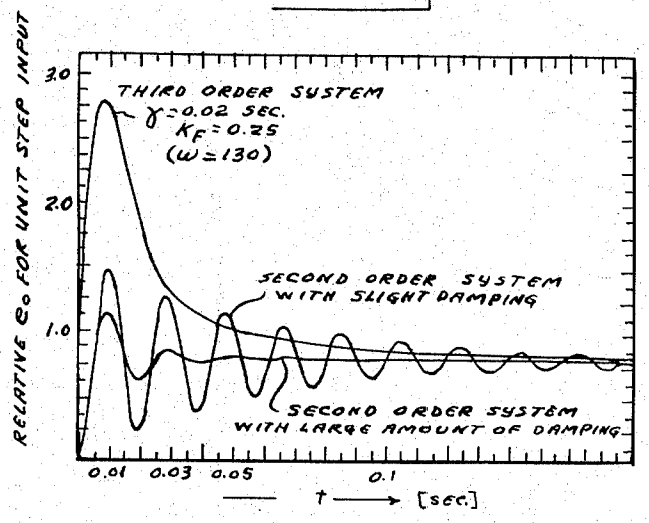
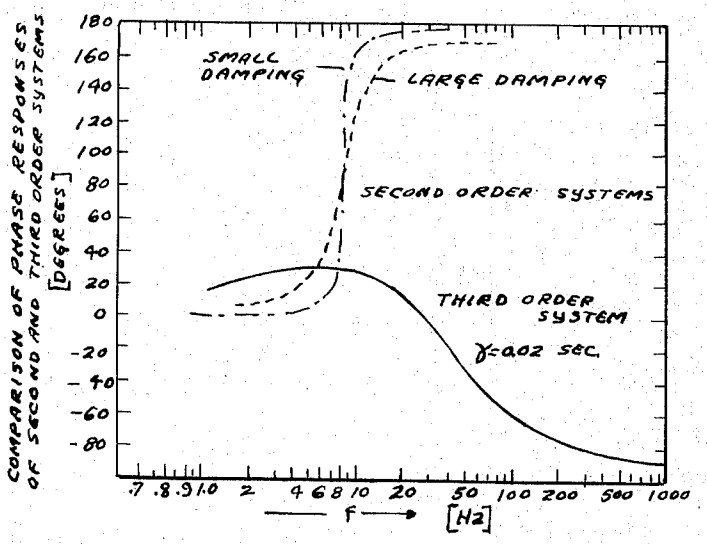


Fig-21



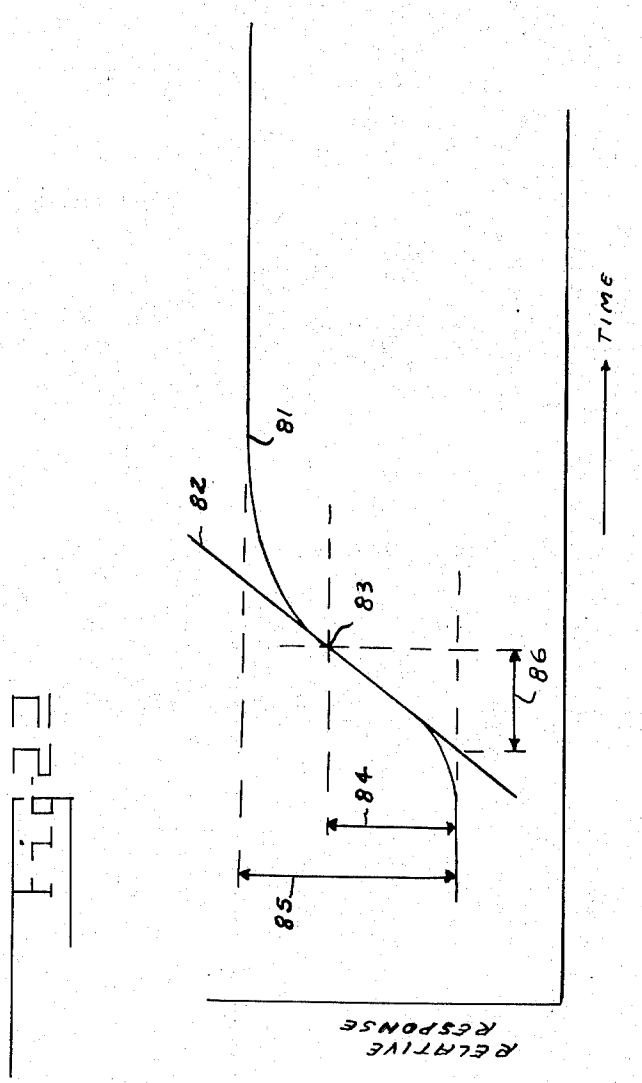


Fig. 22

CONTROLLABLE EDGE SHARPENING SYSTEM FOR TIME SEQUENTIAL SIGNALS

BACKGROUND OF THE INVENTION

The field of this invention is in the electronic signal processing art of time sequential signals.

Lack of edge resolution may show up in images which are reproduced by the utilization of a time sequential signal obtained by electron beam scanning or flying-spot light scanning of photoconductive thin-films and similar phototransducers onto which an optical image is focused. Lack of edge resolution may be due to the finite thickness of the film, finite size of the scanning beam, or unfavorable lateral to transverse ratio of the involved effective resolution element size. Lack of edge resolution may also be due to an insufficient bandwidth in the transmission path, or, the practical physical limitations of elements with respect to wavelength (such as when an optical lens is used in the infrared region of the spectrum). This lack of edge resolution may make it difficult to determine the dimensions, dimension ratios, and exact configurations of imaged objects. Previous attempts to restore the sharpness of the edges have employed a network with appropriate peaking coils and tuned circuits, that is, by the use of ordinary under-damped second order systems. These circuits may improve the sharpness of the edges, but very detrimental post transient oscillations are usually introduced into the signal in an attempt to force sufficient steepness of the edges. Conventional under-damped second order systems cannot produce an overshoot of greater than 100 percent, and achieving even a significant fraction of this has been previously unrealizable in practice. For instance, if post transient oscillations are kept within 2 percent of the steady state value, then in the case of a unit step input, the gained overshoot is less than 2 percent. It is thus evident that an ordinary second order system will not be suitable for any significant edge sharpening. Deteriorated signals, such as signals in which the original unit step inputs have been modified by a first order system, or signals that are deficient in their origin, produce degraded signals which change in a gradual fashion, rather than as a step function. In order to provide sufficient edge sharpening of the signals it is necessary to produce some overshoot, without post-transient oscillations, in the signal. This invention does that, and thus provides usable signals out of generally unusable ones and greatly improved signal resolution out of poor signals.

SUMMARY OF THE INVENTION

The invention, when added to conventional time sequential signal processing equipment, will improve the signal by sharpening the leading and trailing edge characteristics of the signal, removing undesirable noise from the signal, flattening transients that have been introduced onto the signal, and in general will restore a deteriorated signal to essentially the equivalent of its original form. A typical use of the invention is with imaging systems reproducing a picture that has been picked up and transmitted. A picture with a conventional system that appears "smeared" and thus is poorly defined is restored to a sharp picture by the use of the invention. Thus, in a particular instance, target recognition is greatly improved by making target boundaries that were previously indefinite and not precise clear and discernable. Improving target recognition by the third order networks of this invention may not only assure recognition of the target, but will also shorten the time elapsing between seeing the object and perception of what is seen. This can be decisive for videoscreen observation, using light amplifier equipment for low light level aircraft landing, recognition of enemy vehicles and similar usage. In instances where pictures are transmitted over a transmission line with insufficient square wave response, or when the detector system picking up the scene has insufficient intrinsic resolution (such as an optical system with insufficient resolution, or vidicons using semi-conductor target plates which are highly sensitive but which otherwise yield images with insufficient edge sharpness), or where there exists natural poor contrast of target boundary against the background, the invention, by providing a sharp change from black to white in the reproduced image clears up otherwise blurred and smeared pictures. The system of this invention operates in real time without the need of any storage elements or delay means.

BRIEF DESCRIPTION OF THE DRAWING

FIG. **1** shows in simplified block diagram form a typical use of the invention in a typical conventional system;

FIG. **2***a* represents a typical ideal time sequential signal; *b* shows the typical deterioration of the wave of *a* after passing through a conventional first order system;

c shows the effect of the third order system of this invention operating on the wave of *b* to restore it to a wave having suitable characteristics for reproduction;

FIG. **3***a* is a typical plot of a deficient varying time sequential signal at the input to an embodiment of the invention;

b is a plot of the signal of *a* after having passed through the apparatus of this invention;

FIG. **4***a* is a representative plot of a typical time sequential signal essentially obscured by noise at the input to an embodiment of the invention;

b is a plot of the signal of *a* after having passed through an embodiment of the invention;

FIG. **5** is a simplified block diagram of an embodiment of the invention in closed loop transfer function arrangement;

FIG. **6** is a simplified block diagram of an embodiment of the invention in collapsed open loop transfer function arrangement;

FIG. **7** is a block diagram in analog form of the forward part of the loop of FIG. **5**;

FIG. **8** is a block diagram in analog form of the feedback part of the loop of FIG. **5**;

FIG. **9***a* and *b* explain in simplified form the symbols and terminology used in regard to operational amplifiers;

FIG. **10***a* and *b* explain in simplified form the symbols and terminology used in regard to operational summing amplifiers;

FIG. n*a* and *b* explain in simplified form the symbols and terminology used in regard to operational integrators;

FIG. **12**a and *b* explain in simplified form the symbols and terminology used in regard to operational summing integrators;

FIG. 13*a* and *b* explain in simplified form the symbols and terminology used in regard to symbolic potentiometers in the analog circuits;

FIG. 14 is a more detailed block-analog diagram of an embodiment of a closed loop system of FIGS. 5, 7, and 8;

FIG. 15 is a more detailed block-analog diagram of an embodiment of a collapsed open loop system of FIG. 6;

FIG. 16 shows typical frequency responses of embodiments of the invention with various γ time constants;

FIG. 17 shows typical phase responses of embodiments of the invention with various γ time constants;

FIG. 18 shows typical outputs of typical embodiments having an attenuation factor $K_F = 0.25$ with various γ constants for a one-volt unit step input;

FIG. 19 shows typical outputs of typical embodiments having an attenuation factor $K_F = 0.5$ with various γ constants for a one-volt unit step input;

FIG. 20 shows comparative amplitude responses of the third order system of this invention with conventional second order systems to a one-volt unit step input signal;

FIG. 21 shows comparative phase responses of the third order system of this invention with conventional second order systems; and

FIG. 22 shows the determination of the reference circular frequency from a typical S wave type deterioration.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The invention is used in combination with a conventional transmission, reception, and utilization system of time sequential signals as shown in FIG. 1. The first of two major functions of the invention is to improve the leading and trailing edge characteristics of time sequential signals. This is shown graphically in FIGS. 2*a*, 2*b*, 2*c*, and 3*a* and 3*b*. FIG. 2*a* shows an ideal unit step signal as one would like it to be presented to the beam modulation system of a cathode ray tube when scanning (at the transmission end of the system) a black bar against a bright background or vice versa. FIG. 2*b* shows the signal of FIG. 2*a* typically degraded or deteriorated by a first order system, such as occurs, for example in the transmission of the signal over a long uncorrected cable, or as by the signal passing through a system having an insufficient square-wave response, or by any of the other previously enumerated causes. When this signal, as shown in FIG. 2*b*, is used for the modulation of the beam in a cathode ray tube the reproduced image would, instead of changing sharply from black to white (or vice versa), show a very gradual change and would result in the presentation of a smeary picture.

When the signal as shown in FIG. 2*b* is passed through the apparatus of the invention it is typically modified to possess the characteristics shown in FIG. 2*c*. The signal shown in FIG. 2*c* is not congruent with the ideal signal of FIG. 2*a*, which constituted the intensity distribution of one line of scan of the optical image. However, an image produced by the signal of FIG. 2*c* appears on a cathode ray tube (or to any other appropriate device utilizing time sequential signals) as a signal free of smear and a crisp representation of the edges of the imaged object. Visual interpretation of object boundaries in the image will be based on observing the positive and negative peaks P_p and P_n. Comparison of the signal in FIG. 2*c* with the original ideal signal of FIG. 2*a* shows that the time at which the position of the peaks of the output signal of FIG. 2*c* occur in relation to the edges of that of FIG. 2*a* have slightly, and inconsequentially shifted, but that the dimension of the object as represented by the time interval Δt between P_p and P_n and the positive and negative unit step of FIG. 2a has not changed. Of primary significance in respect to the operation of the invention is the fact that no ringing (post transient oscillation) has been introduced as has been common with previous edge sharpening systems.

The second major function of the invention is the substantial removal of noise from a time sequential signal. FIG. 4*a* shows a typical case in which a time sequential signal is practically obscured as a result of being mixed with substantially white noise to such an extent as to be virtually unusable. This signal was fed into an embodiment of the apparatus of the invention and a usable output signal, relatively free of noise, as shown in FIG. 4b was obtained. FIGS. 4*a* and 4*b* are attempted drafting reproductions of photographs of wave traces. Obviously the full detail of the noise cannot be drawn. In the actual wave traces many more random spikes occured in FIG. 4a than could be shown. Photographs of the wave traces would be ideal to include herein, however the prohibition in the use of photographs preclude use of them herein.

The mathematical details of deriving the fact that the required apparatus of this invention has a third order network with a transfer function represented in the Laplace domain by

$$F_R(s) = \frac{e_o}{e_i} = \frac{\dfrac{(1+s\tau_1)}{(1+s\tau_2)(1+s\tau_3)}}{1+K_F\dfrac{(1+s\tau_1)}{(1+s\tau_2)(1+s\tau_3)(1+s\gamma)}}$$

are exceeding long and laborious and will not be included herein. Suffice it to say that a device having this transfer function will produce the results stated herein. Embodiments of apparatus having this characteristic electrical operation using conventional operational amplifiers may be constructed both as a closed loop system as shown in FIG. 5 or as a collapsed open loop system as shown in FIG. 6. Taking first, the closed loop system of FIG. 5, the foregoing transfer function may be rewritten as

$$F_{RC}(s) = e_o/e_i = F_2(s)[/1 + F_1(s)F_2(s)],$$

where

$$F_2(s) = (1+s\,\tau_1)/(1+s\,\tau_2)(1+s\,\tau_3),$$

and

$$F_1(s) = K_F/(1+s\gamma).$$

Then the forward section 11 (of FIG. 5)

$$F_2 = e_o/e_{iF} = (1+s\,\tau_1)/(1+s\,\tau_2)(1+s\,\tau_3)$$

of the closed loop system may be rewritten as

$$e_o = (e_{iF}/s^2)\ (1/\tau_2\tau_3) + (e_{iF}/s)\ (\tau_1/\tau_2\tau_3) - (e_o/s^2)\ (1/\tau_2\tau_3) - (e_o/s)\ [(\tau_2+\tau_3)/\tau_2\tau_3].$$

This is shown in analog operational amplifier symbolic form in FIG. **7**.

The feedback section **12**, (of FIG. **5**)

$$F_1 = e_F/e_o = k_F/(1+s\gamma)$$

of the closed loop system may be rewritten as

$$e_F = (k_F e_o - e_F)/\gamma s$$

This is shown in analog symbolic form in FIG. **8**.

Before progressing further into the circuitry and apparatus of the invention it is desirable that a common reference be established with the reader of this patent in regard to the symbols used since complete uniformity of symbols does not as yet exist in the art. Operational amplifier arrangements performing electronically the common mathematical operations of summing (also subtracting), decade gain changing, multiplying, dividing, integrating, differentiating, and combinations thereof are well known. Generally they consist of a relatively high gain amplifier with a feedback arrangement providing the operational function. The high accuracies of operational amplifiers, their construction, and necessary limitations are well recognized.

In the symbolic representation of operational amplifiers it is generally understood that a polarity inversion of the signal always takes place. That is, an operational amplifier with a negative signal fed into it will provide a signal of positive polarity at its output, and vice versa. Thus an operational amplifier as symbolized in FIG. **9***a* representing a gain changing function provides an understood negative output for a positive signal input. Usually operational amplifiers change the input signal by powers of 10, i.e., 0.1, 1, 10, 100, etc. The more detailed representation as shown in FIG. **9***b* is rarely used but is understood to exist. Thus the symbol as shown in FIG. **9***a* is understood to represent as shown in FIG. **9***b* a relatively high gain direct current amplifier **21**, with an input resistance R_1 and a feedback resistor R_f. The input-output ratio of the signal is determined by the ratio of the feedback resistor to the input resistor as indicated. Generally the result is expressed as an equality rather than an approximation since the result approaches, and for practical purposes is, an equality with high gain amplifiers. (This is really a level changing operation. Note that the term multiplier is commonly reserved for an operational amplifier arrangement with suitable additional components as used to multiply one variable by another variable.) Another operation amplifier used herein is the summing amplifier as conventionally shown in FIG. **10***a* which represents the circuitry shown in FIG. **10***b*. It is to be noted that the summing may be on a unity basis (one-to-one) or at different ratios. FIG. **11**a symbolically represents an integrating operational amplifier more completely detailed in FIG. **11***b*. The integral in the mathematical expression may be expressed with the conventional integral sign or by the use of the Laplace variable *s*. The constant K is generally referred to as the gain of the integrator. An integrator may also be a summing integrator and as used herein is shown symbolically by FIG. **12***a* with the more detailed circuitry of FIG. **12***b* being understood. Another symbol used herein is commonly termed a potentiometer. It is shown in FIG. **13**A. As previously mentioned in operational amplifiers the ratio of input signal to output signal is generally considered to be in powers of **10**. Potentiometer symbols are used to indicate intermediate ratios. Quite frequently, and as done herein, a potentiometer symbol is used to include any order of gain or attenuation. Thus the potentiometer P_7 of FIG. **14** determines a ratio of $\tau_1/\tau_2\tau_3$, which in a particular embodiment of the invention for operation with $\omega_o(2\pi f_o)$ of 100 represents a ratio of 0.10282×10^4. It is thus to be understood that typically in this embodiment this ratio would be achieved as shown in FIG. **13***b* with two operational amplifiers **21** and **22** each of a gain of ×10, a gain of ×100 in the summing integrator **23** and a true physical potentiometer (attenuator) **24** setting the ratio of 1 to 0.103 (necessary tolerances will be defined later). Thus the signal voltage integrated at the integrating operational amplifier **23** is the $-e_{iF}$ signal multiplied by the ratio $\tau_1/\tau_2\tau_3$ or in this specific instance it is $-0.103 \times 10^3 e_{iF}$.

If separate figures in the drawing were used for each specific embodiment the specific required operational amplifiers would be detailed with the required gains shown on the drawing, and the physical potentiometer ratios would also be given on the drawing. However, for simplicity, where a given figure pertains to many different embodiments the potentiometer symbol is used to indicate a variety of level ratios and it is understood to refer to the required apparatus to achieve any particular required value.

The forward section of the closed loop system of FIG. **5** shown in more detail in FIG. **7**, and the feedback section of FIG. **5** shown in more detail in FIG. **8**, are combined in the complete embodiment in FIG. **14**. The collapsed open loop transfer embodiment shown in simplified block form in FIG. **16** is shown in detailed symbolic analog form in FIG. **15**. FIGS. **14** and **15** are detailed to show the circuit operations. It is believed that this is much clearer and more easily understood than attempting to describe the operation of the individual components of the circuits in the text. It can readily be shown that the signal outputs, e_o, from both FIGS. **14** and **15** may be resolved into the fundamental transfer function of e_o/e_i previously set forth. The circuits may be constructed to have a determined fixed amount of edge sharpening with all the time constants, K_F (the attenuation constant), and $1/\gamma$ fixed. For devices with variable, controllable amounts of edge sharpening, K_F is made an adjustable component either in fixed or continuously variable amounts. The embodiment shown in FIG. **14** offers the additional feature of having $1/\tau$ as a similarly variable component. Embodiments having the maximum flexibility and adaptatbility for general use with any system are constructed with suitable, selectable, step ratios in all the potentiometers. The effects of these parameters will be further discussed later. As the circuits are further explained in connection with specific embodiment examples of circuitry, it will be understood that generally the embodiments represented by FIG. **14** will be preferred over those of FIG. **15** for the higher frequency systems. While these circuits may appear rather complex and may involve a relatively large number of circuit elements, modern integrated circuit techniques allow the actual circuits represented herein to be constructed in an extremely small physical size, with the majority of the space requirements taken by the variable control in those embodiments having variable control of the edge sharpening by a separate (such as manual) means.

To construct embodiments of the invention for specific applications there now remains the determination of the numerical values of the constants τ_1, τ_2, τ_3, γ, and K_F. These constants may be derived mathematically for the amount of edge sharpening desired for a particular amount of deterioration in a wave signal. The mathematics is extremely complicated, laborious, and would require many, many pages. Suffice it to set forth there only the required information to indicate the construction of the equipment of this invention for the modification of typical signals to provide the improvements previously stated. By rewriting the foregoing Laplace transfer function in the time domain, and through the proper mathematical manipulation it has been found that three fundamental constants termd ϵ, δ, ρ emerge for all applications of the invention. They have the following relationships.

$$\epsilon = \gamma\omega_o = 2.6$$

$$\delta = \tau_1\omega_o = 10.3$$

and

$$\rho = (\tau_2+\tau_3)\omega_o/2 = 1.48.$$

The following relationships are also derived.

$$\tau_2 = [\rho - (\rho^2-1)^{1/2}]/\omega_o$$

$$\tau_3 = [\rho + (\rho^2-1)^{1/2}]/\omega_o$$

and

$$1/\tau_2\tau_3 = \omega_o^2$$

These expressions present one new term ω_o, the reference circular frequency of the system. It may be readily derived experimentally from the deficient signal (as well as mathematically). Reference is now again made to FIG. **2**, where FIG. **2***a* shows the ideal signal wave (such as scanning from a black area to a white background) and FIG. **2***b* shows an essentially exponentially deteriorated wave (as received through first order systems, which would present a smeary picture). A point **15** on the slowly rising edge of the signal is determined which has an amplitude of 0.632 of the signal maximum **17.** (This figure is not critical in the third place for most applications, 5 percent accuracy is generally sufficient.) The time **18** from the onset of the wave to this point (**15**) is measured, and the reciprocal of this number is multiplied by two to obtain the reference circular frequency ω_o. In an actual embodiment of which FIG. **2** represents the actual circumstances, point **15** occurred approximately 15.4 milliseconds after the onset, thus $(10^3/15.4) \times 2$ gives an ω_o of 130. This value incorporated into the calculations and a typical embodiment constructed therefrom provided the modified signal wave shown in FIG. **2***c* which has an overshoot peak P_P that is approximately 1.85 times the amplitude level of the unit step signal.

Further developing a specific structural embodiment from this figure for ω_o, by using the previously set forth relationships, it may readilly be shown for this particular embodiment having $\omega_o = 130$, that

$$\gamma = e/\omega_o = 2.6/130 = 2.0 \times 10^{-2}$$

$$\tau_1 = \delta/\omega_o = 10.3/130 = 7.9 \times 10^{-2}$$

$$\tau_2 = [1.48-(1.48^2-1)^{1/2}]/\omega_o = 3.0 \times 10^{-2}$$

$$\tau_3 = [1.48+(1.48^2-1)^{1/2}]/\omega_o = 1.98 \times 10^{-3}$$

These values of the constants for an $\omega_o = 130$ apply to both the closed loop embodiments shown in FIG. **14** and the collapsed open loop embodiments shown in FIG. **15.**

Specific typical component parameters are set forth in the following table for three exemplary values of ω_o. They are $\omega_o = 100$, $\omega_o = 130$ (response characteristics for this value will be given later), and $\omega_o = 400$. The value of $\omega_o = 400$ is a typical value for slow-scan picture transmission over telephone lines. Referring first to the embodiment of FIG. **14**:

	$\omega_o = 100$	$\omega_o = 130$	$\omega_o = 400$
P_1, $\tau_2+\tau_3/\tau_2\tau_3$	0.296×10^3	0.38×10^3	0.118×10^4
P_2 and P_6, $1/\tau_2\tau_3$	$\times10^4$	0.168×10^5	0.16×10^6
P_7 $\tau_1/\tau_2\tau_3$	0.103×10^4	0.133×10^4	0.411×10^4
P_4 and P_5, $1/\gamma$	0.386×10^2	0.5×10^2	0.154×10^3
K_F	0.5	0.5	0.5
	0.25	0.25	0.25

The $1/\gamma$ may be made a variable control varying about the value shown with the effects as wil be described later. The attenuation constant, K_F, may likewise be provided as a variable control (effects are shown later) with the typical values of 0.5 and 0.25 shown for reference.

Typically, the values indicated would be achieved as follows:

P_1, two cascaded operational amplifiers each with a gain of 10, a gain of 10 at the input to the summing integrator SI_1 for $\omega_0 = 100$ and $\omega_0 = 130$, and a gain at SI_1 of 100 for $\omega_o = 400$. The ratios set in the physical potentiometer would then be for $\omega_o = 100$, 0.295; for $\omega_0 = 130$, 0.383; and for $\omega_o = 400$, 0.118. For P_2, typically, for $\omega_o = 100$ amplifier A_1 has a gain of 10, the gain at the input to the integrator I_1 is 100, the gain into the summing integrator SI_1 is 10, and a physical potentiometer (if used) is set at unity; for $\omega_o = 130$ A_1 gain is 10, I_1 gain is 100, at SI_1 the gain is 100 and a physical potentiometer is set to 0.168; for $\omega_o = 400$, A_1 gain is 100, I_1 gain is 100, at SI_1 the input gain is 100 and the physical potentiometer is set to 0.16. For P_6, typically, gain of A_2 is 100 for $\omega_o = 100$, $\omega_o = 130$, and $\omega_o = 400$; at $\omega_o = 100$ and 130, gain of I_2 is 10, at $\omega_o = 400$ gain of I_2 is 100, and the gain at the input to SI_1 is 10 for $\omega_o = 100$, and 100 for both $\omega_o = 130$ and 400; the physical potentiometer is set at unity for $\omega_o = 100$, at 0.168 for $\omega_o = 130$, and at 0.16 for $\omega_o = 400$. For P_7 two cascaded operational amplifiers are used each with gains of 10 and the gain into SI_1 is 100 for $\omega_o = 100$, 130, and 400; the physical potentiometer is set to 0.103 for $\omega_o = 100$, to 0.133 for $\omega_o = 130$, and to 0.41 for $\omega_o = 400$. The summing amplifier SA has unity gain for each channel. Typical (mid-range) values for P_4 and P_5, the $1/\gamma$ factor, are composed of gains into the summing integrating amplifier SI_2 of 100 for $\omega_o = 100$ and $\omega_o = 130$, and a gain of 1,000 for $\omega_o = 400$. (For $\omega_o = 400$ it is generally preferable however to use two cascaded operational amplifiers each with a gain of 10 and a gain of 10 into the summing integrator rather than attempt to achieve a gain of 1,000 in one step). By following these examples those skiled in the art may readily construct closed loop embodiments of the invention for any particular situation.

The construction of the open loop, collapsed function, embodiments of the invention as shown in FIG. **15** is made in a similar manner. The following table shows the typical values of the parameters of the circuit for

the same reference circular frequency The results obtained by the two systems. i.e., open and closed loop, are essentially identical. Generally, as will be seen the gains involved in the open loop system are higher, thus it is more difficult from a practical aspect to construct the open loop embodiments at the higher frequencies.

Gain in Circuit	$\omega = 100$	$\omega_o = 130$	$\omega_o = 400$
P-52	0.103×10^{4}	0.133×10^{4}	0.411×10^{4}
P-53	0.497×10^{5}	0.834×10^{5}	0.795×10^{6}
P-54	0.386×10^{6}	0.840×10^{6}	0.247×10^{8}
P-55 (K_F) (typical)	0.25	0.25	0.25
	0.5	0.5	0.5
P-56	0.397×10^{5}	0.667×10^{5}	0.635×10^{6}
P-57	0.214×10^{5}	0.360×10^{5}	0.343×10^{6}
P-58	0.335×10^{3}	0.434×10^{3}	0.133×10^{4}

It has previously been stated that the primary variables of the embodiments for a given ω_o are the attenuation constant K_F and the $1/\gamma$ factor. The following FIGS. **16, 17, 18** and **19** show the effects on a typical embodiment (the previously detailed embodiment for $\omega_o = 130$), of varying these parameters. Generally for this particular embodiment, $\gamma = 0.02$ is the preferred value The amount of edge sharpening desired is then controlled by varying the attenuation constant K_F, with the values of 0.25 and 0.5 being set forth as typical representative values, as shown in the figures. By observing the figures it is readily recognized that the values of the constants are not critical, since more than 100 percent variations of these parameters does not effect the operation of the invention (i.e., instability, erratic operation, etc.), but merely produces a different usable characteristic. The numerical values throughout have been carried out with sufficient accuracy to enable those practicing this invention to easily verify their calculations. They have not been carried out to indicate a criticalness of the value. Generally 5 percent tolerances on all components will be entirely suitable for most applications of the invention.

FIGS. **20** and **21** show comparisons of embodiments of this invention with two prior art second order systems, one with high damping and one with a small amount of damping, as have been previously used in attempts to achieve the results of this invention. FIG. **20** shows the ever present ringing efect in the prior art devices, wih the total absence of it in the present invention. It is also to be observed in FIG. **20** that very little overshoot can be obtained when the oscillations (ringing) are kept to a usable value as shown in the highly damped second order curve.

FIG. **21** shows a phase comparison of prior art systems with a typical system of this invention. All the systems of FIG. **21** are designed for operation in the area of $f_o = 20$Hz, (i.e., an ω_o of approximately 130). The remarkable stability and smooth characteristics of the present invention over the rapidly changing characteristics of prior art systems are very apparent. This curve alone shows the vast improvement in operation gained through the apparatus disclosed herein.

Previous reference was made to the experimental determination of ω_o from the exponentially deteriorated wave signal shown in FIG. **26.** For other types of deterioration, such as are frequently encountered in many transistor and other types of systems, the deterioration produces an S type curve such as curve **81** of FIG. **22.** Since the determination of ω_o is not extremely critical a sufficiently close determination for the majority of systems may be made by drawing a straight line **82** along the slowly rising onset of the wave and determining a point **83** which is approximately 63 percent of the step height, i.e., length **84** is approximately 63 percent of length **85.** The time interval **86** is then used as previously set forth to determine the preferred reference circular frequency of the system to be used for improving the signal.

We claim:

1. An edge sharpening system for improving the signal characteristic of time sequential electronic signals comprising:

a. means for providing a signal input to the said system;

b. means including a summing integrator for providing a signal output from the said system;

c. means for providing a first feedback loop feeding a determined ratio of the said output signal into the said summing integrator;

d. means for providing a second feedback loop integrating the opposite polarity of a determined ratio of the said output signal and feeding the resultant signal into the said summing integrator;

e. means for providing a third feedback loop providing an intermediate feedback signal that is the integral of the sum of a determined ratio of the said output signal and a determined ratio of the said intermediate feedback signal;

f. means, in the said third feedback loop, for summing the said intermediate feedback signal and the said system input signal providing a summed signal;

g. means, in the said third feedback loop, for feeding a determined ratio of the said summed signal into the said summing integrator; and

h. means for feeding the integral of a determined ratio of the said summed signal into the said summing integrator.

2. An edge sharpening system for improving the signal characteristics of time sequential electronic signal comprising:

a. means for providing a signal input to the said system;

b. means for providing an output signal from the said system;

c. a first summing integrator;

d. a second summing integrator;

e. a third summing integrator;

f. means for inverting the polarity of the said system input signal and feeding the inverted input signal into the said first summing integrator;

g. means for feeding the said system output signal into the said first summing integrator;

h. means for feeding a determined ratio of the said system output signal into the said first summing integrator;

i. means for feeding a determined ratio of the said system input signal into the said second summing integrator;

j. means for feeding a determined ratio of the output of the said first summing integrator into the said second summing integrator;

k. means for feeding a first determined ratio of the opposite polarity of the said system output signal into the said second summing integrator;

l. means for feeding a second determined ratio of the opposite polarity of the said system output signal into the said second summing integrator;

m. means for feeding a determined ratio of the opposite polarity of the said system input signal into the said third summing integrator;

n. means for feeding the output of the said second summing integrator into the said third summing integrator; and

o. means for feeding a determined ratio of the said system output signal into the said third summing integrator.

3. A controllable edge sharpening system for improving the signal characteristics of time sequential signals comprising:

a. means for providing a signal input to the said system;

b. means for providing a first summing integrator providing a signal output from the said system;

c. means for providing a first feedback loop feeding a determined ratio of the said output signal into the said summing integrator;

d. means for providing a second feedback loop integrator the opposite polarity of a determined ratio of the said output signal and feeding the resultant signal into the said summing integrator;

e. means for providing a third feedback loop comprising;

1. a variable attenuator cooperating with the said system output signal providing a plurality of selectable ratios of the said output signal;

2. means cooperting with the output of the said variable attenuator for providing a first variable ratio of signal into the said means to signal out of the said means;

3. means for providing a second variable ratio of signal into the said means to signal out of the said means, substantially identical to, and ganged with the said first variable ratio means so that substantially equal ratios are always provided in both the said first and second variable ratio means;

4. means for providing a second summing integrator having as inputs the output of the said first variable ratio means and the output of the said second variable ratio means, and the output of the said second summing integrator being the input to the said second variable ratio means;

5. means for summing the said output of the said second integrator means with the said input signal to the system;

6. means for feeding a determined ratio of the output of the said summing means into the said first summing integrator means; and

7. means for integrating a determined ratio of the opposite polarity of the output of the said summing means and feeding the resultant signal into the said first summing integrator means.

4. A controllable edge sharpening systemm for improving the signal characteristics of time sequential signals comprising:

a. means for providing a signal input to the said system;

b. means for providing an output signal from the said system;

c. a first summing integrator;

d. a second summing integrator;

e. a third summing integrator;

f. means for inverting the polarity of the said system input signal and feeding the inverted input signal into the said first summing integrator;

g. means for feeding the said system output signal into the said first summing integrator;

h. a variable attenuator cooperating with the said system output signal providing a plurality of selectable ratios of attenuation of the said system output signal;

i. means for feeding the output of the said variable attenuator into the said first summing integrator;

j. means for feeding a determined ratio of the said system input signal into the said second summing integrator;

k. means for feeding a determined ratio of the output of the said first summing integrator into the said second summing integrator;

l. means for feeding a determined ratio of the opposite polarity of the output of the said variable attenuator into the said second summing integrator;

m. means for feeding a determined ratio of the opposite polarity of the said system output signal into the said second summing integrator;

n. means for feeding a determined ratio of the opposite polarity of the said system input signal into the said third summing integrator;

o. means for feeding the output of the said second summing integrator into the said third summing integrator; and

p. means for feeding a determined ratio of the said system output signal into the said third summing integrator.

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