A SYSTEM FOR MEASURING STEADY-STATE TORQUE ON A ROTATING SHAFT

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16. ABSTRACT

The report describes a system to transfer torque signals from a rotating shaft to stationary equipment using a transformer concept. The system has error correcting capabilities to eliminate drift. The system has been successfully used on large generators and pumps. Includes 8 figs, 2 refs., 15 pp.

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A SYSTEM FOR MEASURING STEADY-STATE TORQUE ON A ROTATING SHAFT

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Denver, Colorado

SI METRIC

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In May of 1981, the Secretary of the Interior approved changing the Water and Power Resources Service back to its former name, the Bureau of Reclamation. All references in this publication to the Water and Power Resources Service should be considered synonymous with the Bureau of Reclamation.

CONTENTS

FIGURES

INTRODUCTION

A system for measuring steady-state torque on a rotating shaft has been developed using a transformer technique rather than conventional slip rings to couple the signal off the shaft. The system comprises a small battery-operated sensing unit riding on the shaft and a stationary signal processing unit for recording and indicating the results. The equipment is easy to install and is compensated for drift in the signal processing circuits.

CONCLUSIONS

1. Satisfactory drift compensation has been achieved allowing steady-state torque measurements to be made on a rotating shaft.

2. The system is relatively easy to use because slip rings are not required. It has been used successfully on shafts from 100 to 2500 millimeters (4 inches to 8 feet) in diameter and with as little as 50 mm (2 in) of exposed shaft available.

APPLICATION

The torque measurement system was developed for the purpose of determining the feasibility of making a real-time mechanical input power measurement by sensing shaft torque as a measure of prime mover mechanical input power. The device evolved from earlier use of the same principle to sense shaft torsional oscillations [1]*; however, it is useful as a strain indicator for any type of strain measurement including static or rotational.

GENERAL DESCRIPTION

As shown on figure 1, the system is divided into two parts. One part (fig. 1A) rides on the shaft and the other (fig. 1B) is stationary.

Shaft torque is measured using a strain gage bridge comprising four active strain gages oriented to sense torque[2]. The bridge output, after amplification by an instrumentation amplifier, frequency modulates a voltage controlled oscillator **VCO** making the signal medium a variable frequency. The **VCO** output is converted to low duty cycle relatively high current pulses which are easily transformer coupled off the shaft to the stationary processing unit. This signal coupling method obviates slip rings, resulting in easier and more universal application with low battery drain.

Two major sources of error in a system of this type are d-c amplifier drift and **VCO** frequency drift. Compensation for both error sources is inherent in the encoding-decoding scheme used here. Drift, due to the temperature coefficient of the strain gages, is compensated by the symmetry of the full bridge configuration.

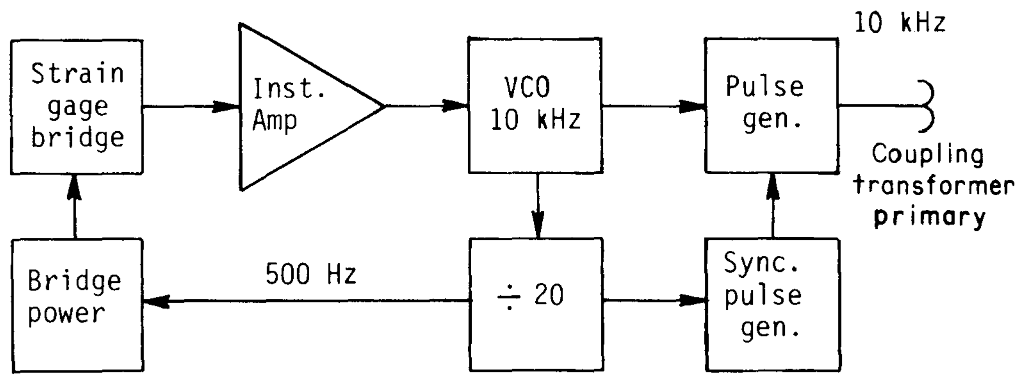
The effect of amplifier zero drift and **VCO** frequency drift is avoided by interrupting the bridge d-c excitation at a 500-Hz rate. The 500-Hz modulation frequency is derived by dividing the 10-kHz **VCO** frequency by 20, thus preventing undesirable beat frequencies between the **VCO** and bridge excitation signals. The slight frequency variation of the bridge excitation when the **VCO** is modulated by the strain signal does not affect the measurement system output. The strain information is contained in the frequency difference occuring when the bridge is alternately excited then unexcited. This frequency difference is determined only by the bridge unbalance multiplied by system gain if the drift rates are slow compared to the modulation period. The receiver demodulator converts the variable frequency pulses back to a square wave while the synchronizing circuits keep the decoder square wave in phase with the corresponding 500-Hz bridge power waveform. Two sample-hold circuits continuously monitor the excited and unexcited system outputs respectively while a difference amplifier responds only to the resulting difference in the two levels. The difference amplifier output just described is thus a d.c. level proportional to shaft torque. The error sources associated with strain gage torque transducers are well documented in the literature and will not be discussed here.

CIRCUIT DESCRIPTION

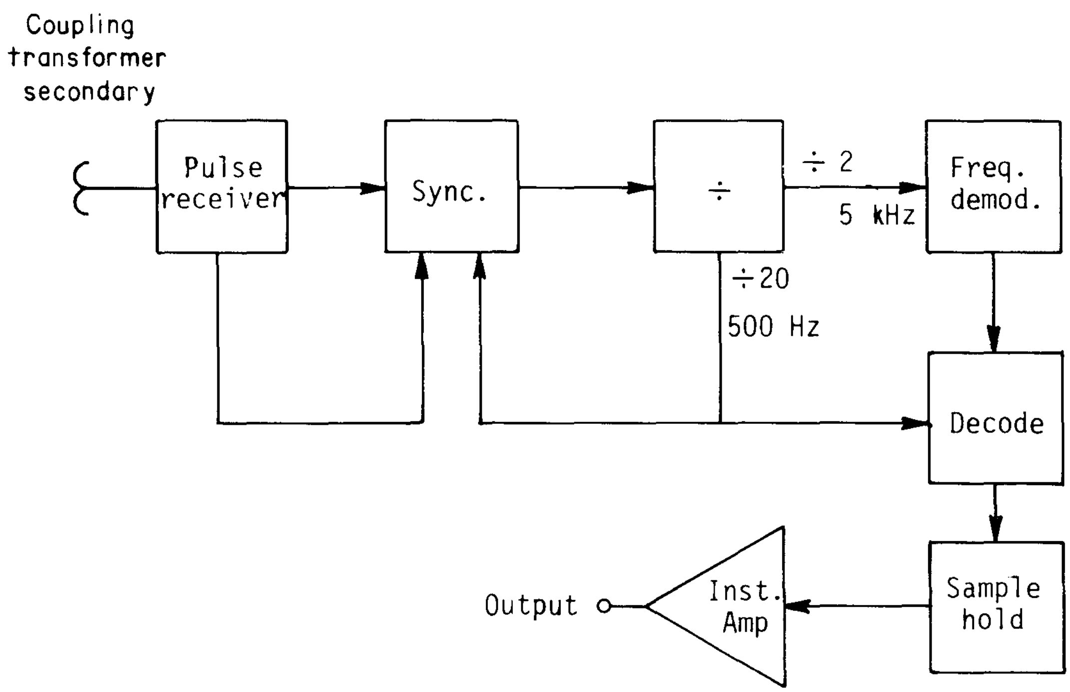
Strain Gage Bridge

The strain gage arrangement is a full bridge configuration (fig. 2). In other words, all four strain gages are active, resulting in increased sensitivity

* Numbers refer to the bibliography.



A



B

Figure 1. — Block diagram of complete system.

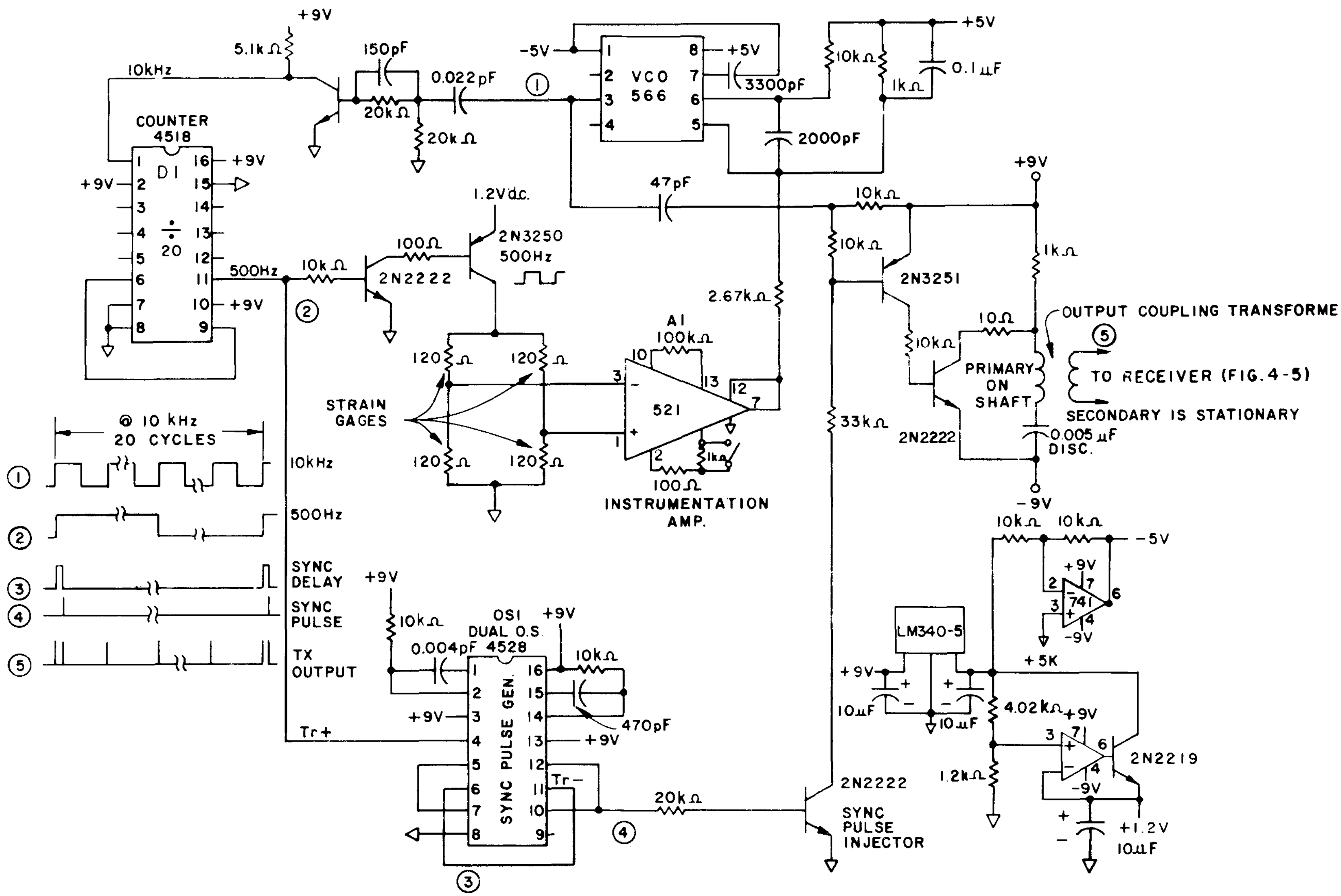


Figure 2. – Torque sensor, encoder, transmitter.

to torque. This configuration produces optimum temperature compensation of the bridge including eliminating the effects of all strains other than torsion.

Bridge Amplifier
(refer to fig. 2)

The bridge difference amplifier **A1** is a **521** integrated circuit instrumentation amplifier having a differential input impedance of a 3×10^9 ohms and a common mode input impedance of 6×10^{10} ohms making the effect of amplifier loading of the bridge negligible. The amplifier gain is 100 or 1000 and its output is the control voltage input of a **566** voltage controlled oscillator **VCO** operating at nominally 10 kHz. The frequency modulation sensitivity of the **VCO** is approximately 4.6 kHz/V and is linear.

Pulse Generator
(refer to fig. 2)

The square wave output of the **VCO** is differentiated via the 47-pF capacitor and the negative going transition momentarily turns on a complimentary transistor pair, discharging a 0.005-μF capacitor through the primary of the output coupling transformer resulting in waveform 3**A** (fig. 3).

Bridge Excitation
(refer to fig. 2)

The 500-Hz bridge excitation signal (fig. 3**B**) is generated by dividing the 10-kHz **VCO** signal by 20. The resultant 500-Hz square wave drives a transistor switch, coupling the strain gage bridge to a 1.2-V d.c. regulated voltage source. When the bridge is balanced, equal 500 Hz square waves are coupled to the two inputs of the instrumentation amplifier, resulting in zero volts d.c. out of the amplifier. Any unbalance of the bridge causes the amplifier output to alternate between a d.c. level proportional to the bridge unbalance, and a zero reference output when the bridge is unexcited. Of course, this amplifier output is a 500-Hz square wave causing the **VCO** to alternate between a zero reference frequency f_1 and a shifted frequency f_2, proportional to bridge unbalance. Thus the signal information is contained in the frequency difference $f_2 - f_1$ which is not affected by zero drift of the amplifier or frequency drift of the **VCO**.

Synchronizing (sync.) Pulse Generation
(refer to fig. 2)

A synchronizing pulse (fig. 3**D**) is generated by a dual one-shot multivibrator (**OSI**, fig. 2). The positive going transition of the 500-Hz square wave described above triggers a delay one-shot multivibrator (**OSI**, fig. 2) which in turn triggers the second half of the dual one-shot. The second one-shot output (fig. 3**D**) constitutes a synchronizing pulse which is sandwiched into the pulse train (fig. 3E) delivered to the output coupling transformer primary. The sync. pulse ensures that the measurement system output polarity will always correspond to the sense of the applied torque that is positive voltage out for positive applied torque.

Pulse Receiver
(refer to fig. 4)

Figure 4 is a composite block diagram of the receiver decoder. The pulse receiver (figs. 4 and 5) is a discreet transistor, **FET** input amplifier. The transistors are hooked as a complimentary pair with negative d.c. feedback for bias stability; however, the bias resistors are bypassed at the signal frequency to allow adequate gain. An **NPN** transistor interfaces the receiver with the **74121 TTL** one-shot multivibrator. The one-shot output delivers constant amplitude, constant width pulses (fig. 3F) to the sync. card.

Synchronizer Card
(refer to figs. 4 and 6)

The purpose of the synchronizer card is to generate a 500-Hz square wave and synchronize it to the 500-Hz bridge excitation signal in the transmitter. The 500-Hz bridge excitation signal (fig. 3**B**) is generated by dividing the 10 kHz **VCO** output by 20. The required 500-Hz signal for the decoder (fig. 3**H**) is generated in a similar way. The 10-kHz pulse train out of the receiver (waveform **F**, fig. 3) is divided by 20 also. However, the sync. pulse must be removed from **F** before applying this pulse train to the divider **D1** (figs. 4 and 6). The sync. pulse is removed by **OSI**, a one-shot with its pulse length adjusted a little wider than the sync. delay (fig. 3**C**). This results in constant amplitude, constant width pulses (fig. 3**G**) to the divider **D1** (fig. 4 and 6) with the sync. pulses removed. The divider **D1** has two outputs. One is a *divide-by-2* output (5 kHz) which goes to the demodulator and a *divide-by-20* output (500 Hz) for the decoder. An additional requirement remains that the 500-Hz decoder square wave must be synchronized in phase with the 500-Hz bridge excitation in the transmitter. Synchronization is accomplished as follows (figs. 3 and 4): The sync. pulse (fig. 3**D**) follows a positive transition of the bridge excitation signal (fig. 3**B**) by a fixed delay determined by a delay one-shot (**OSI**, figs. 2 and 3**C**). A similar

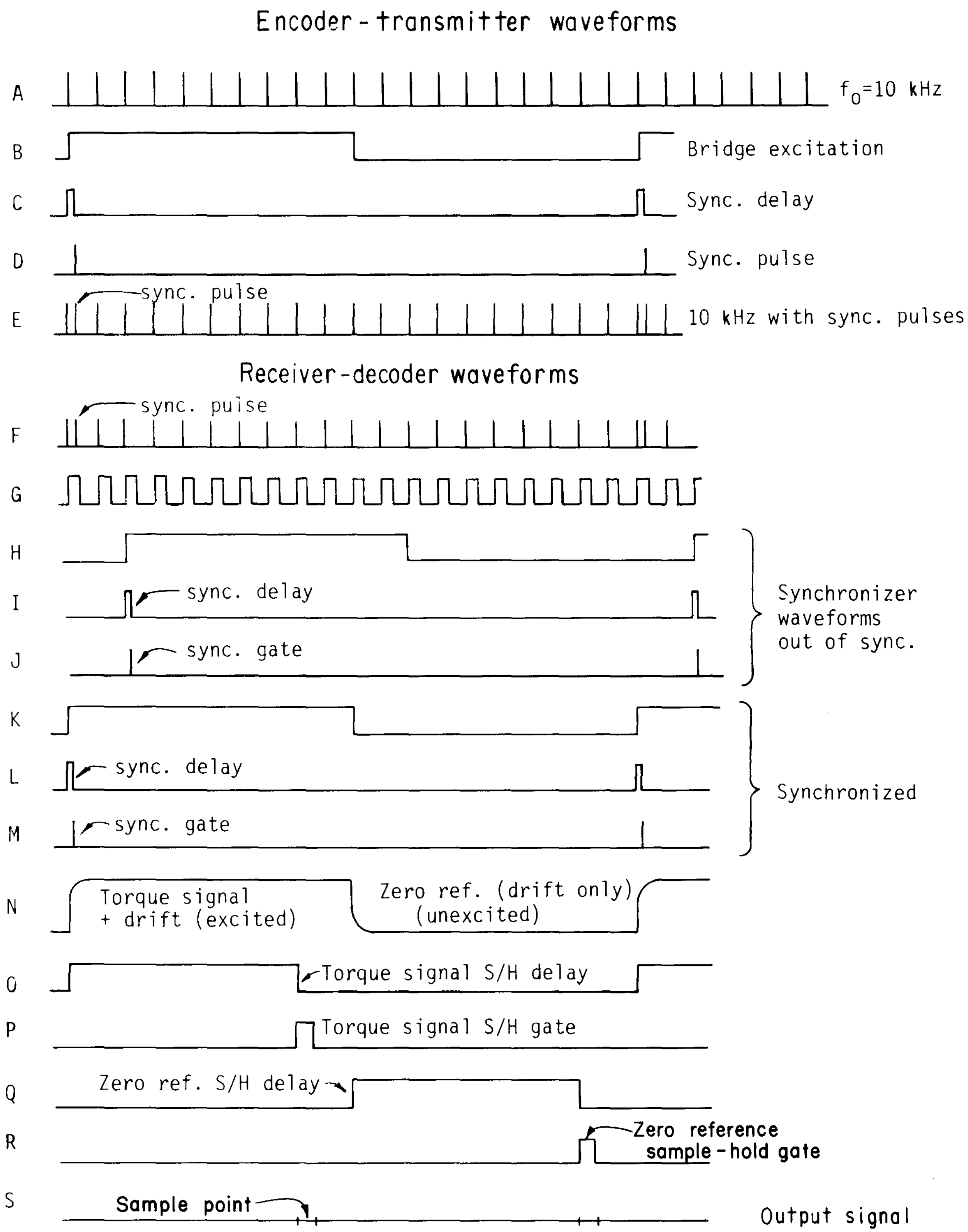


Figure 3. — Waveforms.

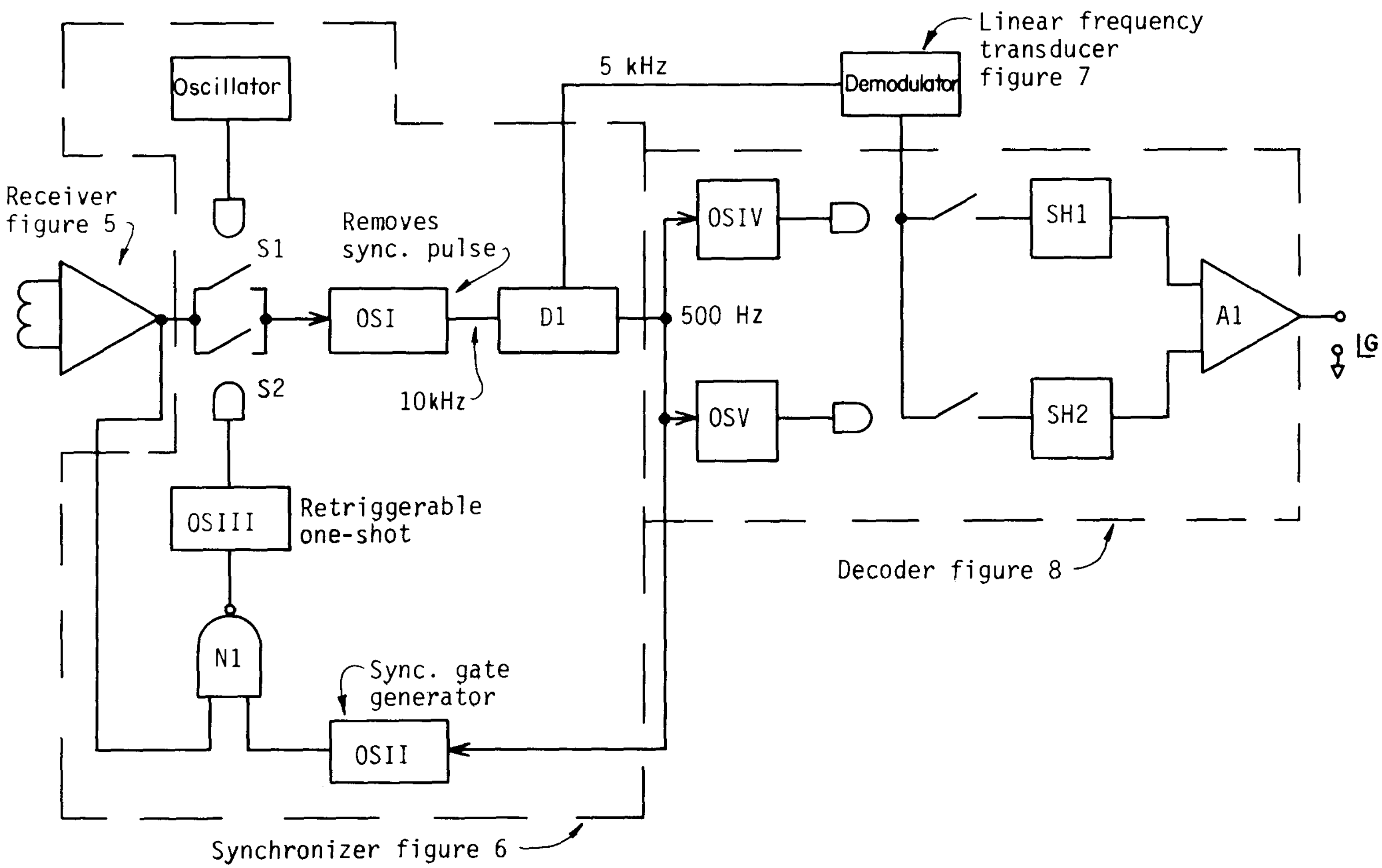


Figure 4. — Receiver-decoder block diagram.

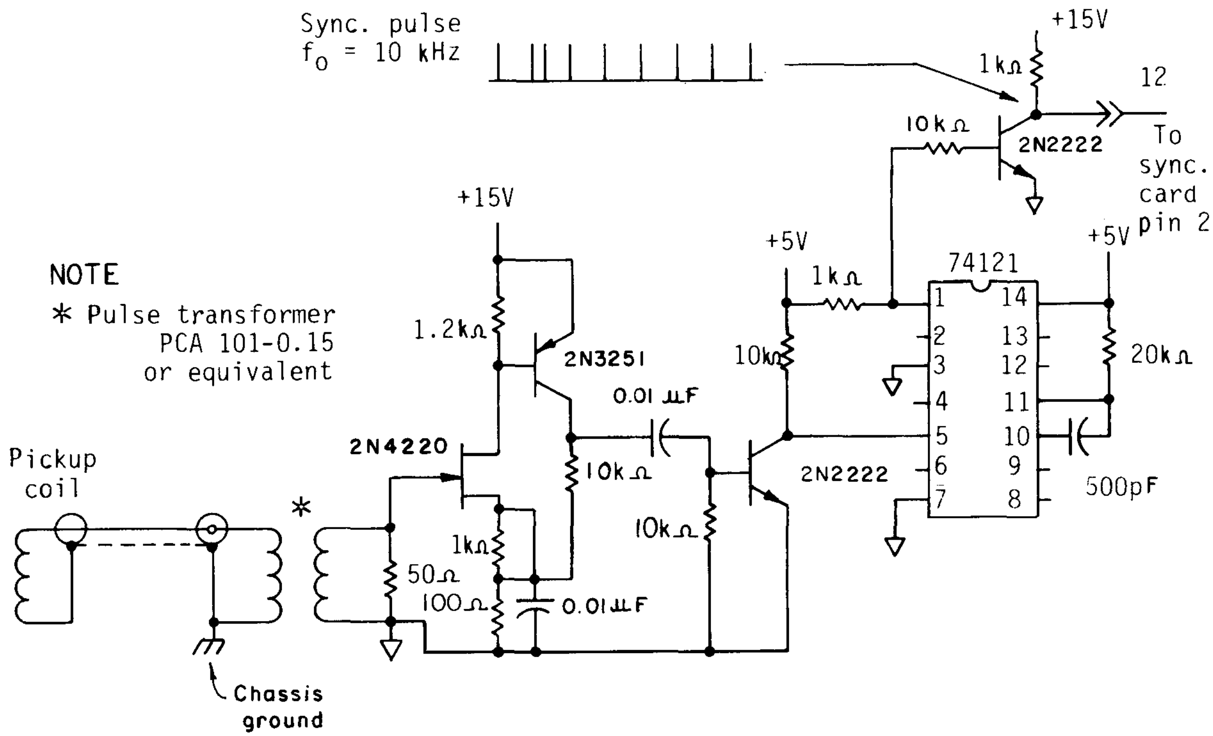


Figure 5. — Receiver schematic.

Note: The sync. search **OSC** periodically removes the incoming signal causing the 500-Hz synchronizer signal to assume a new phase relation to the 500-Hz signal of the transmitter. The proper phase relation is detected by a nand gate when the incoming sync. pulse is coincident with the 500-Hz sync. gate. When the two 500-Hz signals are synchronized properly, the nand gate output triggers a retriggerable one-shot and bypasses the search **OSC** interrupt switch.

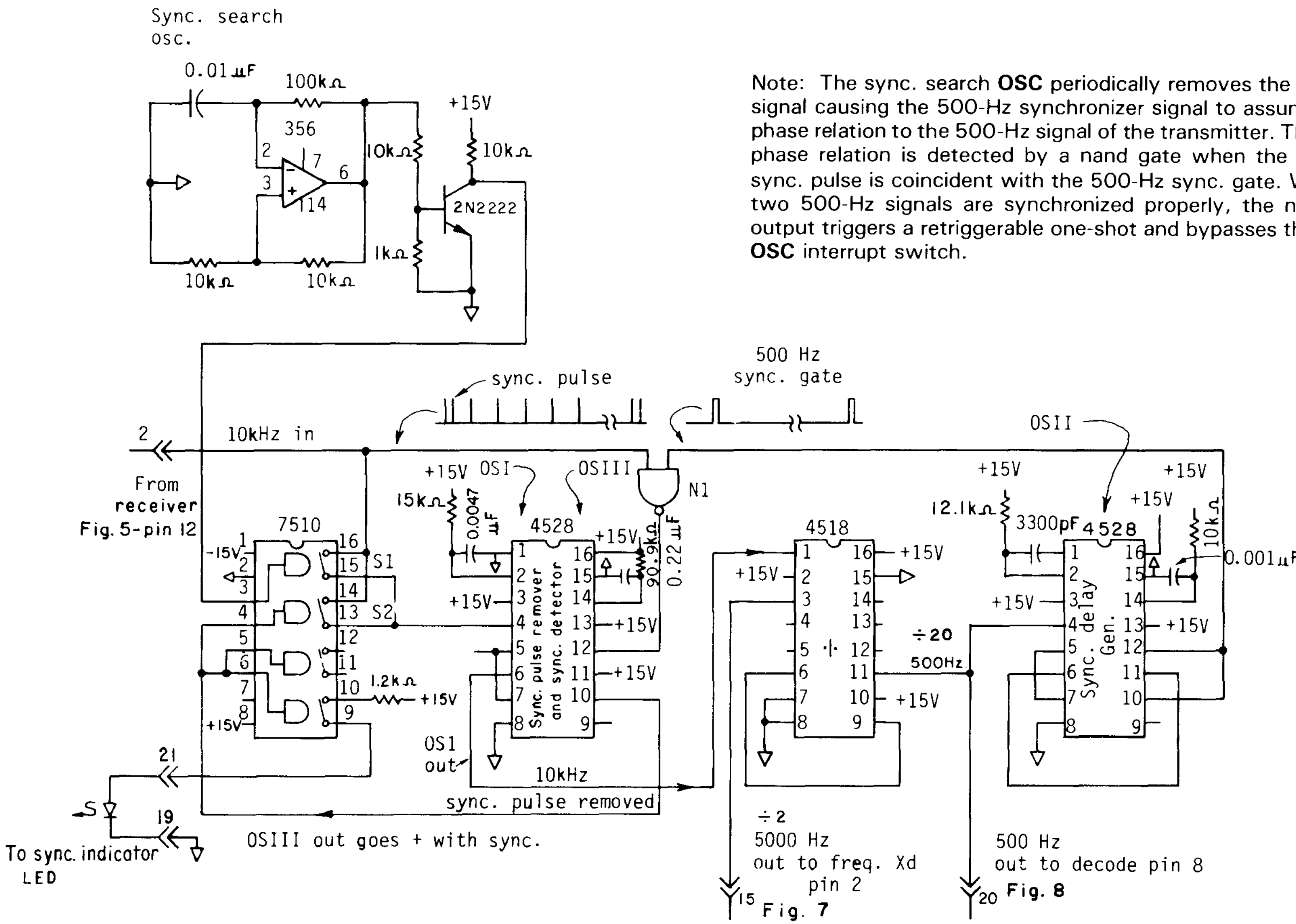


Figure 6. — Synchronizer schematic.

pulse (fig. 3J) is generated by **OSII** (fig. 4) in the synchronizer circuit and is delayed an equal amount after the positive transition of the 500-Hz square wave **H** of the synchronizer. This second delayed pulse **J** is called the sync. gate. The 500-Hz bridge excitation signal (fig. 3**B**) and the 500-Hz square wave in the synchronizer (fig. 3**K**) are synchronized properly when the sync. pulse **F** and sync. gate **M** are coincident. Coincidence is detected by a nand gate **N1** (figs. 4 and 6) and the nand gate output triggers a retriggerable one-shot **OSIII** which in turn closes switch S_2 (figs. 4 and 6). If the pulses described above are not coincident, there are no pulses out of the nand gate **N1**; therefore, the retriggerable one-shot **OSIII** output stays low and S_2 remains open. With S_2 open, the free running oscillator driving S_1 alternately opens and closes the signal path causing the relative phase of the two previously described 500 Hz squares waves to vary. When proper synchronization occurs (the pulses **D** and **M**, fig. 3, become coincident), the retriggerable one-shot **OSIII** (figs. 4 and 6) output goes high, closing S_2 which maintains the signal path and the two 500-Hz square waves are synchronized. The high output of **OSIII** lights an LED indicating proper synchronization. The 500-Hz square wave (figs. 3**K** and 6) out of the synchronizer is used to time the two sample-hold gates of the decoder properly. The 5-kHz output of the synchronizer is routed to the frequency demodulator, a linear frequency transducer (figs. 4 and 7). The frequency transducer output alternates between zero volts while the strain gage bridge is unexcited (corresponding to the zero reference frequency of the **VCO**) and a voltage proportional to the bridge unbalance when the bridge is excited (corresponding to the shifted frequency of the **VCO**). The signal of interest is the difference in voltage between the excited and unexcited levels out of the frequency transducer (waveform **N**, fig. 3).

Frequency Transducer
(refer to figs. 4 and 7)

The frequency transducer receives the 5-kHz variable frequency signal (fig. 4) from the synchronizer card and converts it to a d.c. level proportional to frequency. The conversion is accomplished by using the 5-kHz square wave (waveform **A**) as the gate signal via **AS1-b** of a gated integrator **I1** (fig. 7). The output of the integrator is a linear ramp (fig. 7 waveform **B**) during the half period while the gate switch is closed. The final value of the ramp at the end of the half period is the desired level that is sampled and retained by a sample-hold circuit **SH1**. The integrator then is reset via **AS1-a** to be ready for the next half period. Waveform **C** and **D** (fig. 7) are the sample and reset timing signals, respectively. The d.c. output voltage of the frequency transducer sample-hold circuit is a function of **VCO** frequency; however, a frequency transducer of this type inherently is nonlinear. The frequency transducer is linearized using an analog divider **D1** (fig. 7) as shown below. An expression for the rate of change of voltage across the integrator **I1** capacitor is

$$dV/dt = i/C, \text{ volts per second} \tag{1}$$

where i is the charging current and C is the capacitance.

Since i and C are constant in this circuit, dV/dt is constant, making the integrator output voltage proportional to the time $T/2$ which is a half period of the 5-kHz input signal. Therefore, the capacitor voltage at the end of a half period is

$$V_c = i/C\,(T/2) = KT, \text{ volts} \tag{2}$$

where $K = i/(2C)$.

The 5-kHz waveform period T can be expressed as

$$T = 1/f, \text{ seconds} \tag{3}$$

where f is the frequency (nominally 5 kHz).

Substituting 3 into 2 gives

$$V_c = K/f, \text{ volts} \tag{4}$$

indicating the nonlinear characteristic of this type of frequency transducer. Voltage V_c then is delivered to an analog divider which has an output voltage of

$$V_o = 10x/y, \; y > 0 \tag{5}$$

where x is a constant and $y = K/f$.

Therefore, the linearized frequency transducer output is

$$V_o = K'f, \text{ volts} \tag{6}$$

where $K' = 10x/K$.

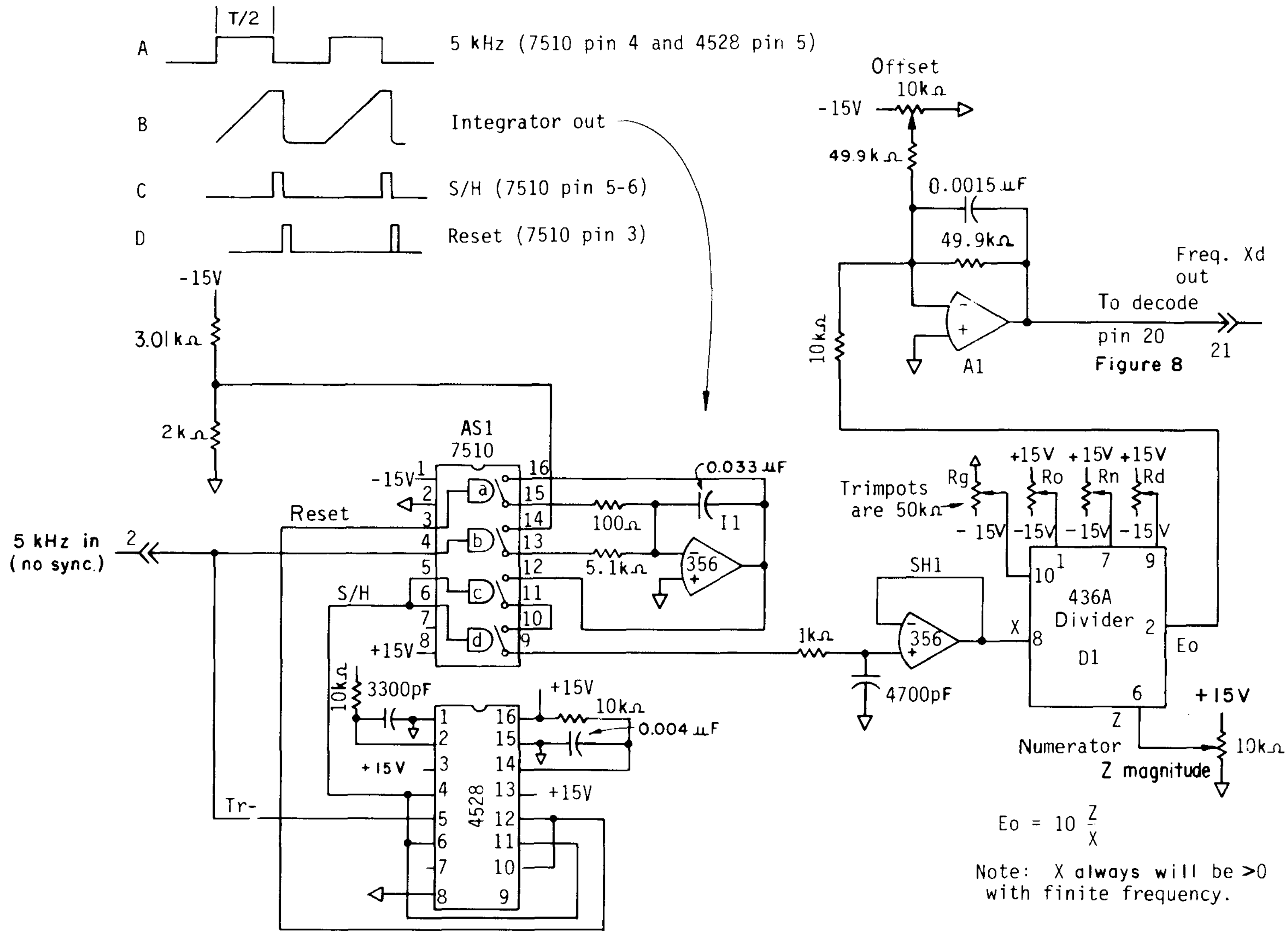


Figure 7. — Frequency transducer schematic.

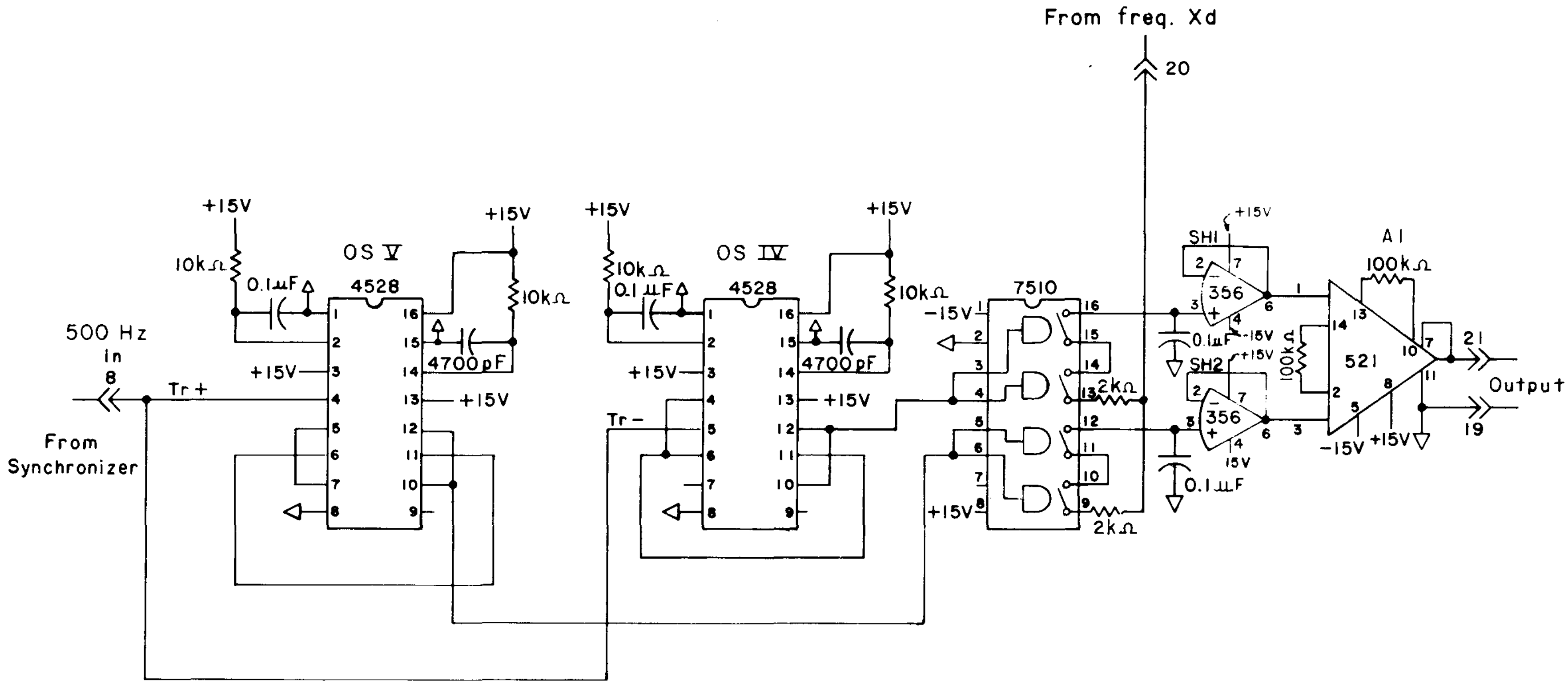


Figure 8. — Decoder schematic.

Decoder
(refer to figs. 4 & 8)
The frequency transducer output (fig. 3**N**) and the 500-Hz square wave (fig. 3**K**) are routed to two different sample-hold circuits (**SH1** and **SH2**). Sample-hold **SH1** samples during the excited portion of the bridge power waveform and the **SH2** during the unexcited portion. Proper timing for the sample gates is derived by triggering delay one-shots (**OSIV** and **OSV**) at the beginning of the respective excited and unexcited portions of the 500-Hz decoder square wave using the positive transition to trigger **SH1** and the negative transition for **SH2** (fig. 3, waveforms **O, P, Q, R**).

The output of **SH1** is a d.c. level proportional to signal + drift and **SH2**'s output is proportional to drift alone. Amplifier **A1** responds to **SH1** – **SH2** which corresponds to (signal + drift – drift) **G** where **G** is the gain of **A1** (figs. 4 and 8). The output of **A1** is a d.c. level proportional to torque.

CALIBRATION

There are no calibration adjustments once the overall system gain is decided upon. The gain, of the bridge amplifier in the sensor section, is shown having two switch selectable values. This feature is needed only if the maximum torque expected would saturate the system. The overall system gain in the high sensitivity position of the switch mentioned above is on the order of 10 000. Calibration can be affected by applying a known torque – if possible – or by unbalancing the bridge a known amount by applying high value known precision resistors across appropriate pairs of the strain gages and noting the output shift. Then the output can be measured while the input is calculated. Various commercial calibration schemes are available also.

The procedure for adjusting the analog divider should follow the recommendation of the manufacturer. This would be a one-time "factory adjustment" and is not difficult.

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