1972

Design and test an operational amplifier speed transducer

Tung-Ming Huang

DESIGN AND TEST AN OPERATIONAL AMPLIFIER SPEED TRANSDUCER

BY

TUNG-MING HUANG, 1944

A THESIS

Presented to the Faculty of the Graduate School of the

UNIVERSITY OF MISSOURI-ROLLA

In Partial Fulfillment of the Requirements for the Degree

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

1972

Approved by

Virgil J. Flanigan (Advisor)   R. T. Johnson

James W. Joiner

ABSTRACT

This thesis describes the design of an angular speed transducer. The purpose of this device is to provide a D.C. voltage which is proportional to the angular speed of a rotating shaft at any instant.

The speed of the shaft is defined from a magnetic pickup monitoring a gear or similar device attached to the end of the shaft of a piece of rotating equipment. The signal from the magnetic pickup is modified and compared to a frequency generated in the feedback loop of the speed transducer and the error is sent to an integral type controller. The output of the controller is directly related to the speed of the shaft.

The system is designed as a feedback control system and compensation techniques can be applied if required by the system applications.

ACKNOWLEDGEMENT

The author wishes to acknowledge Dr. V. J. Flanigan for his direction and advice in the development of this measuring system.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

Figure Page

I. INTRODUCTION

The work described in this thesis is to design an angular velocity measuring system. In motor or engine driven systems it can be necessary to have a device to measure the angular velocity of the motor or other driven components in order to control the system functions. The measuring system must be able to define the steady state value as well as follow any speed change. Also the loading caused by the measuring system should be as small as possible. The measuring system presented in this thesis is intended to fulfill the previous criteria.

There are systems developed which will measure angular velocity accurately without excessively loading the system, but they have been lacking in dynamic ability.

The system here designed is a continuation of the work of Perrson [1] reported in 1970. The design consists of a normal feedback control system with frequencies being compared and integrated to produce a D.C. level representing speed. This D.C. level is sampled and fed to a D.C. level to frequency convertor to produce the feedback signal. This control system design and test will be discussed.

II. BACKGROUND INFORMATION

A short discussion of basic angular velocity measuring systems will now be presented.

A. D.C. Tachometer Generator

The D.C. Tachometer Generator is similar in appearance and operation to the D.C. motor. A fixed field is established with a D.C. current flowing through a fixed coil. As the rotor windings cut the constant magnetic field, a voltage is generated in the rotor windings which is proportional to the velocity. The transfer function can be written [2]:

$$\frac{E_0}{\theta} = K_s S$$

$$E_0 = K_s \omega$$

where: S is the Laplace transform operator and

K_s is the D.C. generator gradient in volts per radian second [3].

This device is, probably, the most commonly used in control systems and has an advantage in that it continuously monitors the speed of the rotating shaft.

Tachometer generators have the following problems: the necessity for brushes and commutation, they exhibit friction, produce both electrical and radio noise, and are subject to drift and quite often a varying K_s. Even more important is the loading of the device which can be very large when the device is initially engaged due to the inertia of the armature of the D.C. tachometer generator. For example, if a D.C. tachometer generator is applied to a small servo motor, the servo motor will respond to the change in load and generally slow down. But if the same tachometer would be applied to a diesel engine the speed change from the actual system before engaging and after, would be very small.

B. Timer-Revolution Counter

This device consists of a revolution counter and timer, both are started and stopped by the same switch. To obtain the angular velocity the number of revolutions is divided by the time interval the device was counting. This device makes it possible to obtain good average speed figures. However, instantaneous speeds are not obtainable due to the time interval. If for example, the angular velocity of the shaft being measured has a constant level plus a superimposed sinusoidal, the sinusoidal, if of high frequency, would not be noticed and the device would display closely the constant level only.

C. Stroboscopic Speed Measurement

If a single mark is made on a shaft, and an adjustable flashing light is adjusted so that there is one very short flash per revolution. The frequency of the flashing light is a direct speed indicator and is used by adjusting the flashing frequency until the rotating mark appears to stand still. The frequency of the flashing light is the rotational speed of the shaft.

Of course, a rotating mark will also appear to stand still if the shaft speed is any multiple of the flash frequency. For example, a single mark on a shaft which is revoluting at 200 rps will make two revolutions between flashes if the flashes are at the rate of 100 per second, and also 50, 25, etc. There is a technique for eliminating the harmonics and determining the actual shaft speed. This is accomplished by gradually increasing the frequency of flashing light from a low value until apparent stopping of the rotating member occurs. Note the frequency of flashing, and then increase the flash frequency to double the first value. If there still is only one apparent stationary image, again double the frequency. Continue until two 180 degree images appear at one of the doubled frequencies. When these two images first appear, the flash frequency is twice the speed of rotation.

Although the accuracy is high and there is virtually no loading, the device is very poor for measuring changing speeds because the operator has to change the flash setting in order to keep the object stationary.

D. Vibrating-Reed Tachometers

This device consists of a set of thin reed-like cantilever members. The reeds may all be the same length, but by adjusting the mass at the free end of each, the natural period of vibration of each is adjusted until a set of reeds are lined up in the order of their natural period. When the frame of the tachometer is placed in mechanical contact with the frame of a rotating machine, and when there is a small unbalance in the machine, the reed with the natural frequency closest to the frequency of the machine vibration will respond the most readily. Note that this type of tachometer does not require a connection to rotating shaft, or even that the rotating shaft be visible. Of course, if another source of vibration is present besides the rotating unbalance, the meter may give a double indication. Also, with a well-balanced machine, there may not be a strong enough vibration present in the frame to energize the reeds.

E. Mechanical Tachometer

A typical mechanical tachometer consists of a centrifugal device, usually a small eccentric balance weight restrained by a spring. The speed is determined by measuring the force required to restrain the eccentric weights against centrifugal force.

Usually this device has a slow response, damping out any high frequency speed fluctuations. Additionally the loading of the device is typically large.

F. Frequency to D.C. Level Transducer

Perrson [1] developed a speed measuring system which takes advantage of a frequency produced by a magnetic pickup monitoring a gear attached to the shaft of interest.

A magnetic pickup is mounted next to a gear which has been affixed to the rotating shaft. When the shaft is rotating, an approximate sinusoidal signal is generated by the magnetic pickup. The magnitude of this signal then is clamped to a certain voltage and drives a constant current through a feedback capacitor of an input operational amplifier producing an output voltage ramp that increases in magnitude until bounded. The slope of the rise and fall is essentially constant. The trapezoidal wave form produces pulses of current through an absolute circuit and then flows into the feedback capacitor of the output operational amplifier and converts it into a D.C. output voltage.

Since the output amplifier smooths the pulses, the output voltage is proportional to frequency alone.

This measuring system has a continuous input but the electrical system converts this signal to digital type current pulses. If the measuring system was operated on a continuous input signal and did not convert it into digital form, the system performance would be improved. For example, for a step frequency change, the response is a function of the number of current pulses that are necessary to charge up the capacitor to the average value of the current pulses.

Perrson suggested a system which consists of a D.C. level to frequency convertor and an integrator to provide a D.C. level. The D.C. level to frequency convertor is in the feedback loop and provides a frequency to compare with the input frequency. This allows the structuring of a classical feedback control circuit with the ability to change controllers for the desired performance. This is the problem that has been worked in this experiment.

III. SYSTEM PRESENTATION

A. System Structure

The measuring system was to be designed to measure the angular velocity of a rotating shaft, the shaft must be long enough to allow the mounting of a magnetic pickup and a gear. Or for that matter, a spur gear, sprocket, or any magnetically permeable material with discontinuities can be used, that may already be affixed to the machine. The only other job would be the mounting of the magnetic pickup.

The block diagram representing the overall measuring system is presented in figure 1. The limiter, integrator and absolute value circuit are necessary to obtain a wave which is independent of the amplitude of the output of the magnetic pickup (ω_i) but a function of the frequency of incoming signal. In the feedback loop the D.C. level to frequency convertor is used to generate a frequency according to the positive D.C. level which is stored by the integrator in the feedforward path. Again the output (ω_f) of D.C. level to frequency convertor is sent through a limiter, integrator and absolute value circuit to make the feedback signal (b) independent of amplitude but dependent upon the frequency of the feedback frequency (ω_f).

The output of the system (C) is the D.C. level stored in the integrator of the feedforward path and it can be scaled to represent speed.

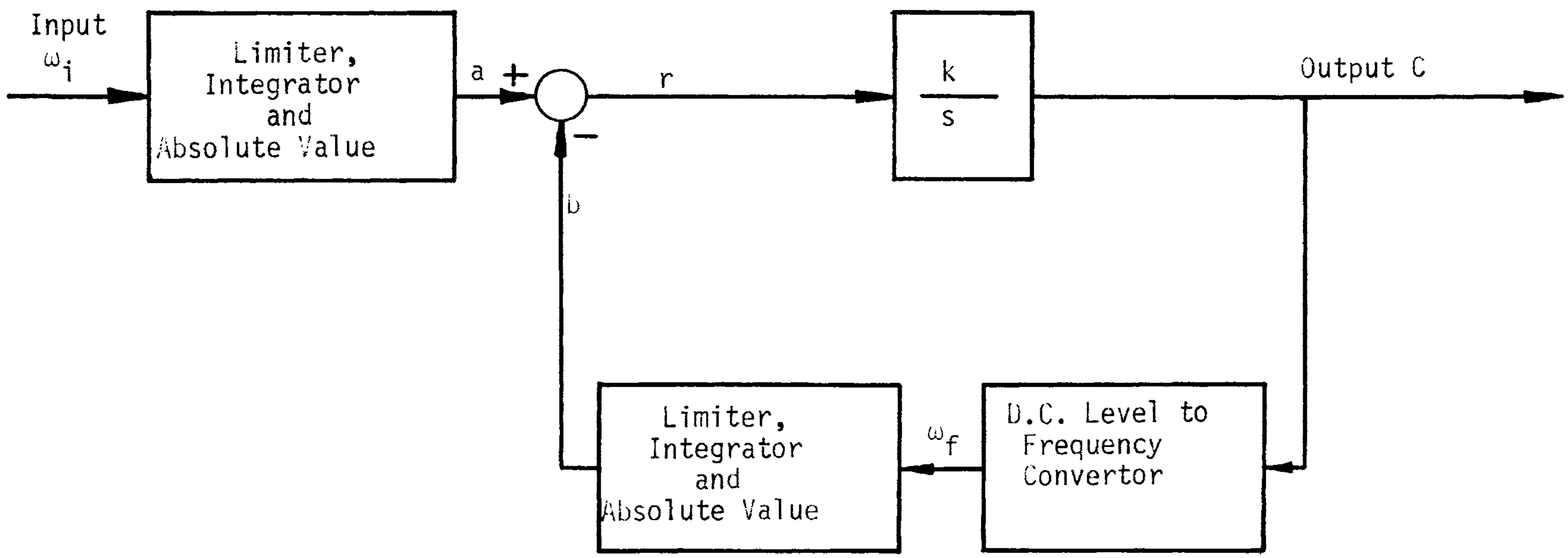


Figure 1. Block Representation of Measuring System

B. System Design

1. Limiter, Integrator and Absolute Value Circuit

The first circuit (figure 2) of the system operating on the input sine wave (ω_i) and also in the output wave (ω_f) from the D.C. level to frequency convertor is a Limiter, Integrator and Absolute Value Circuit. The output of this circuit is a wave, whose amplitude is a function of the frequency of the incoming signal. The limiter has a 10 gain on it because usually magnetic pickups have output voltages of 0.1 to 1 volt, the 10 gain allows for a better voltage range for using the analog components.

The amplitude of the incoming signal is limited by the clamping circuit (amplifier 1), an essentially constant voltage is maintained across it. The next step is to integrate the sine wave or approximate sine wave (amplifier 2) to produce a signal whose amplitude is frequency dependent. The integration of $A\sin\omega t$ produces $(A/\omega)\cos\omega t$ which produces the frequency dependency necessary. The integration of the sine wave is difficult because of the bias present in a real circuit. In order to avoid this bias driving the amplifier into overload a feedback signal is applied. During system operation the feedback pot is set at 0.9. This proved to be the best setting for good stable operation. This operation is defined by the transfer function:

$$\frac{E_o}{E_i} = \frac{1.1111}{1 + 0.0011\,S}$$

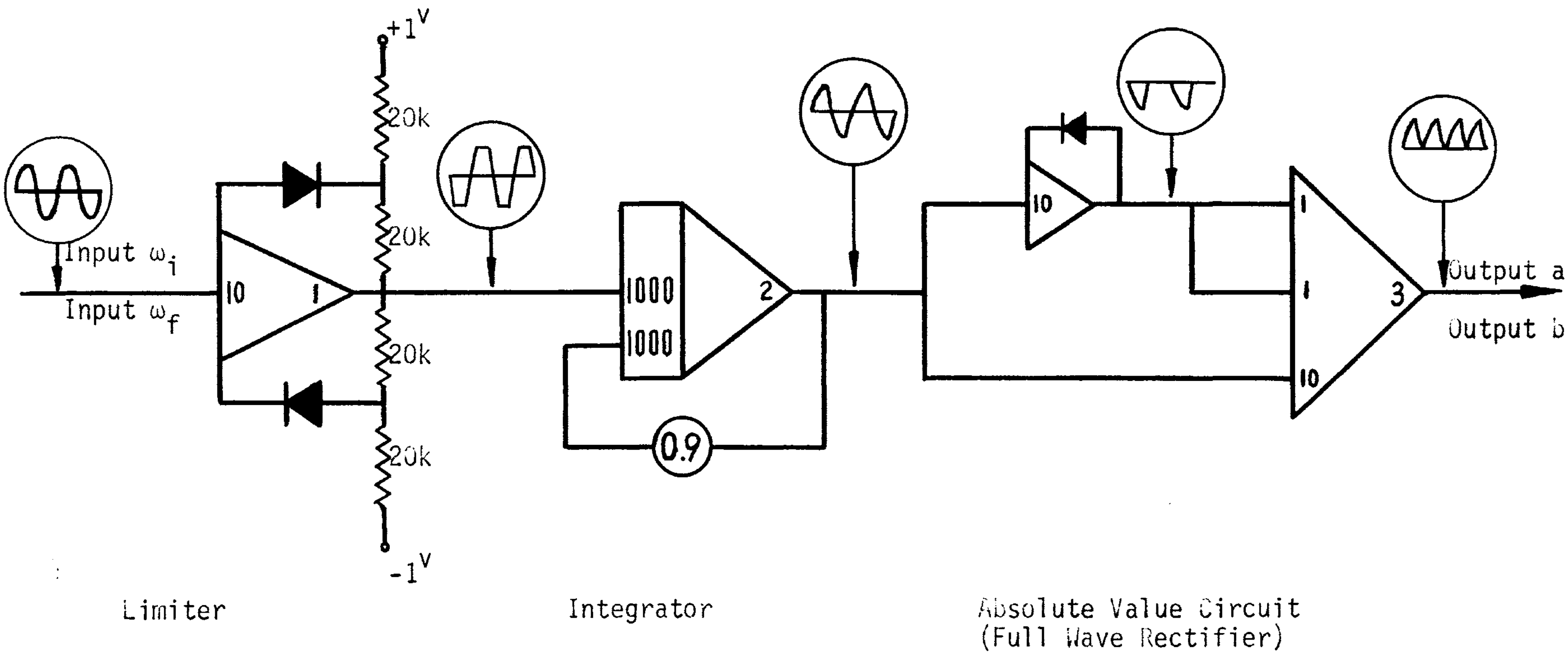


Figure 2. Limiter, Integrator and Absolute Value Circuit

To produce an error between the input frequency and feedback frequency the absolute value of each of these signals must be taken because the mean value of a sine wave is zero. For better accuracy full wave rectification is performed.

2. D.C. Level to Frequency Convertor

A fast acting D.C. Level to Frequency Convertor [4] is shown in figure 3.

Assume initially that the system is in the Initial Condition mode, and assume the state of the comparator, 19, is in logic 0, so that the electronic switches are turned off. Thus the output of amplifier 7 is -1 unit (minus reference voltage). Since the integrator's initial condition is zero, the net comparator input is negative, that is, the state of the comparator is logic 0.

When the system is in the Compute mode, the switches remain turned off. Thus the output of amplifier 7 remains at -1 unit, and integrator 6 integrates upward. The rate of integration is made proportional to the input X. Once integrator 6 reaches +1 unit, it overcomes the negative bias on the comparator, 19. This causes the comparator output to become logic 1, turning on the switches. The output of amplifier 7 is now +1 unit (plus reference voltage) and the net integrator input is +X voltage. So that the integrator integrates downward. When the integrator output reaches -1 unit, it overcomes the positive comparator bias and turns the switches off. The integrator (amplifier 6) then integrates upward.

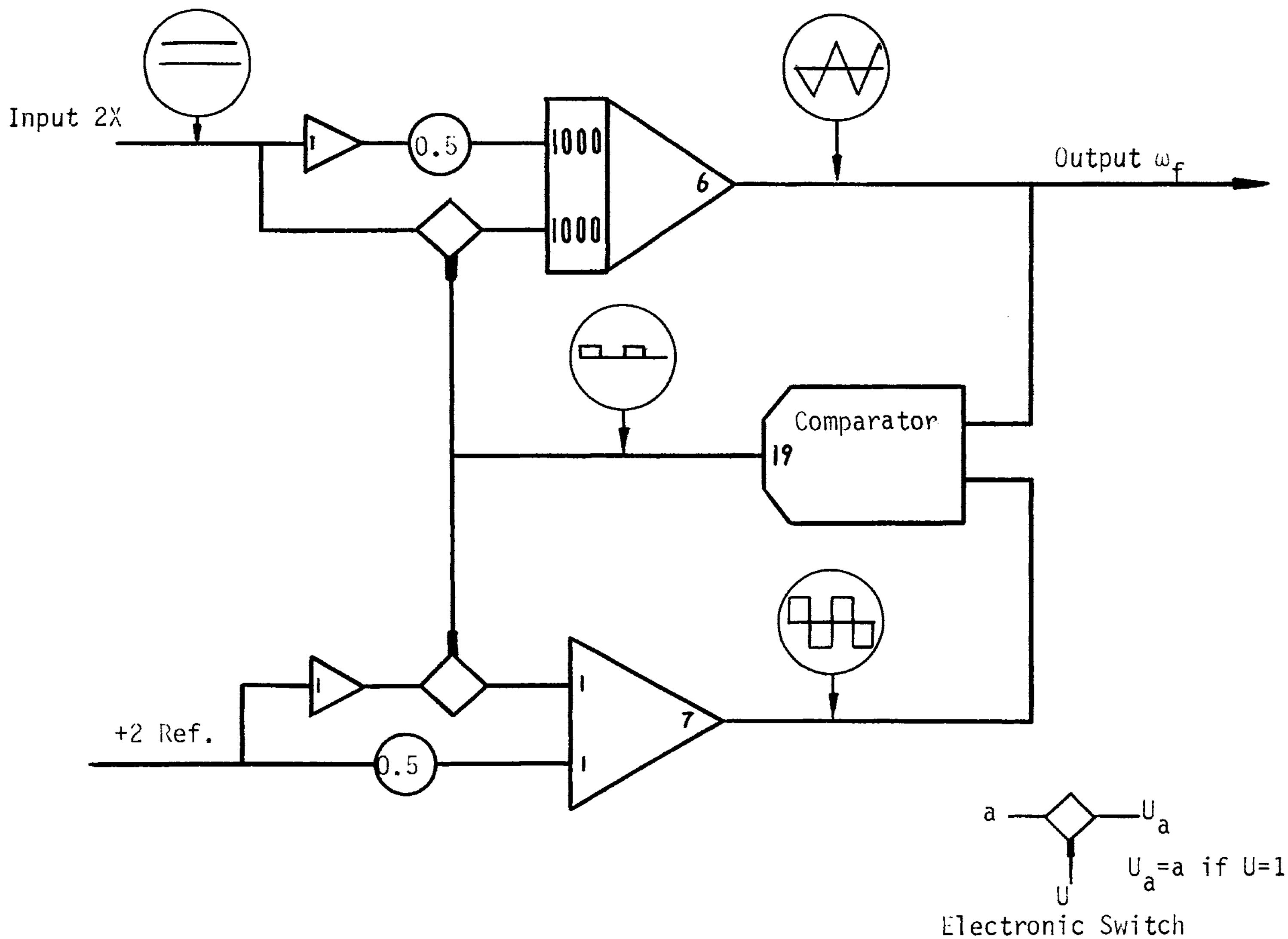


Figure 3. D.C. Level to Frequency Convertor Circuit

It should be pointed out that the input to the integrator (amplifier 6) (figure 3) can be $\pm X$ but it is assumed that X will be plus or zero. The output of amplifier 7 (figure 3 and 4) is oscillating between ± 1 unit regardless of X at a frequency of the output of the integrator (amplifier 6). The amplitude of the output of the integrator (amplifier 6) is determined by the magnitude of ± 1 unit which is set as a function of the reference voltage (figure 3).

In order to define the production of the output frequency, ω_f, from the D.C. level to frequency convertor let a period begin at time t_1 and end at time t_2, then

$$\int_{t_1}^{t_2} X dt = 4 \text{ units.}$$

That is

$$(t_2 - t_1)X = 4$$

hence the period $t_2 - t_1 = 4/X$ and the frequency is $X/4$. This is the case assuming that the gain of integrator (amplifier 6) is 1.

The circuit produces a triangular wave, a square wave and a logic signal, all with the same frequency. The wave shapes are given in figure 4.

If it is initially assumed that the state of the comparator, 19, (figure 3) is in logic 1, then the system will start computing downward.

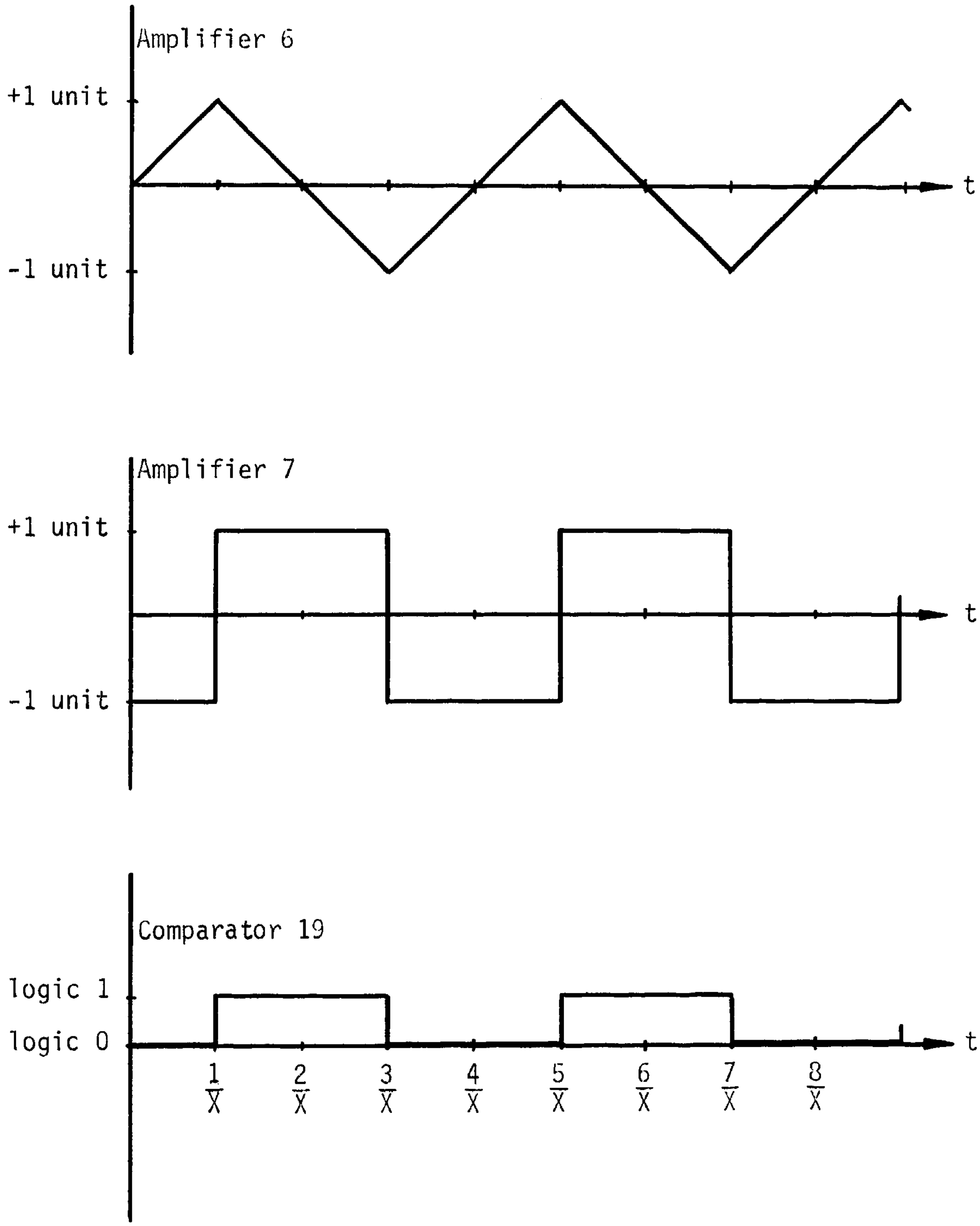


Figure 4. Waveshapes for D.C. to Frequency Convertor

If the gain of integrator (amplifier 6) is G, the frequency is then GX/4, thus the circuits maximum frequency is only limited by G.

Since the input X must be greater than or equal to zero, this circuit requires a positive signal to produce a frequency. This requires a signal start-up procedure which will be discussed later.

C. Construction of the Overall Measuring System

The speed transducer consists of four groups of devices (figure 5), the input signal is modified by system 1 (Limiter, Integrator and Absolute Value Circuit) which limits, integrates and takes the absolute value of the input. The modified input, a, is compared to the feedback signal, b, (figure 5) and integrated in system 2 (Comparator and Integrator). The output of system 2 is the D.C. level representing speed C. This D.C. level is then sent to system 3 (D.C. to Frequency Convertor), whose output is a frequency corresponding to the input level. This frequency is modified in system 4 (Limiter, Integrator and Absolute Value Circuit) in the same fashion as the input signal and its output, b, is compared to, a, to produce the error function, r. The device is required to minimize the error, r, due to the amplitude changing being modified by the integration of the input signal and feedback frequency signal.

Again for operation, initial conditions are applied (figure 5) to integrator 5 to insure the frequency convertor starts in the proper direction since as previously pointed out it can only operate with a positive input. Without this initial condition the initial

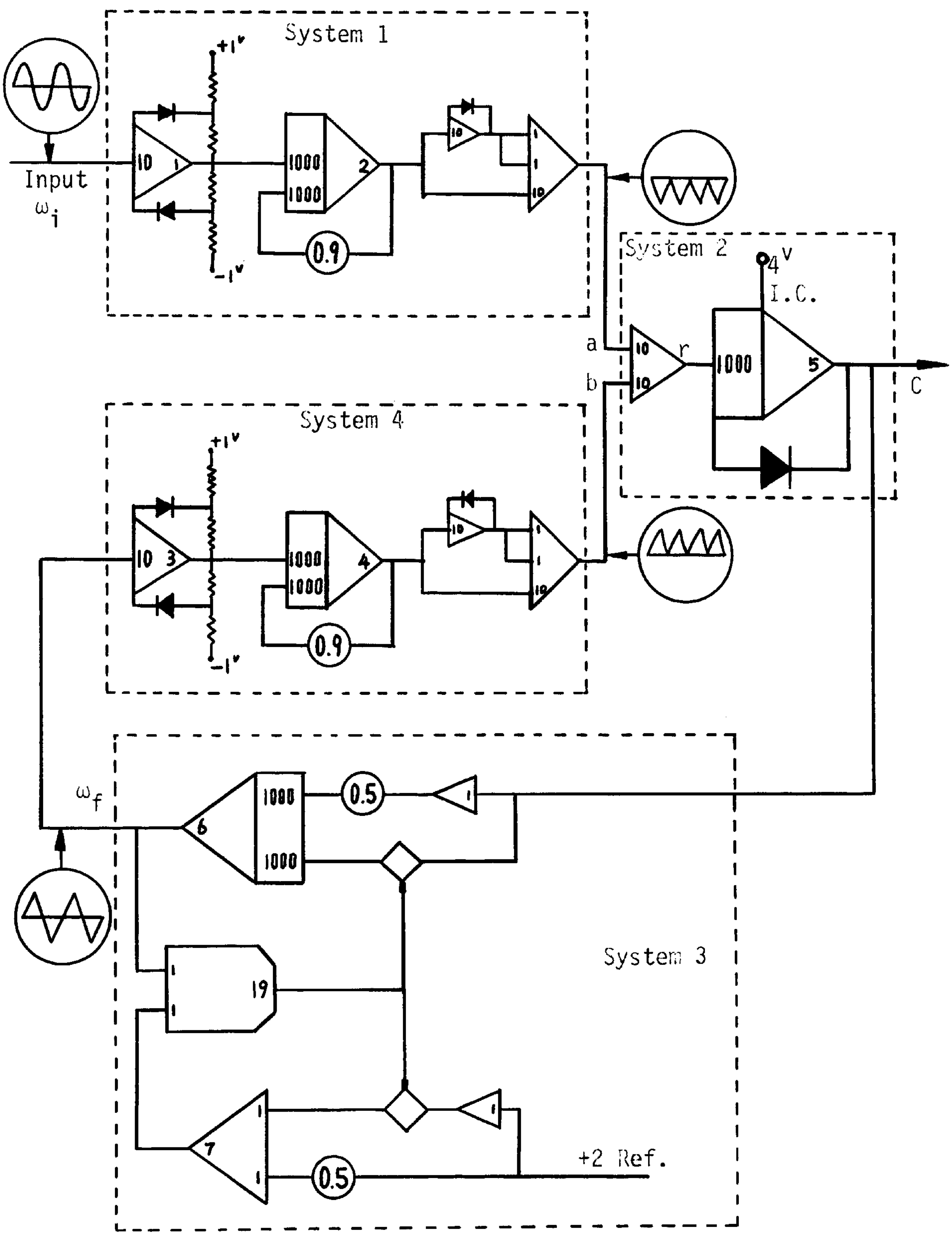


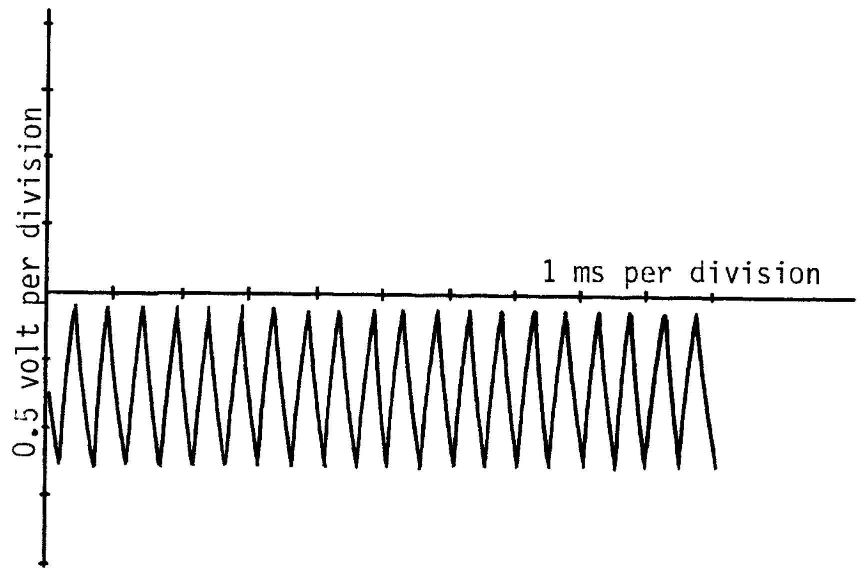
Figure 5. Circuit Schematic of Overall Measuring System

error would produce a negative output, C, which would not allow system 3 to perform.

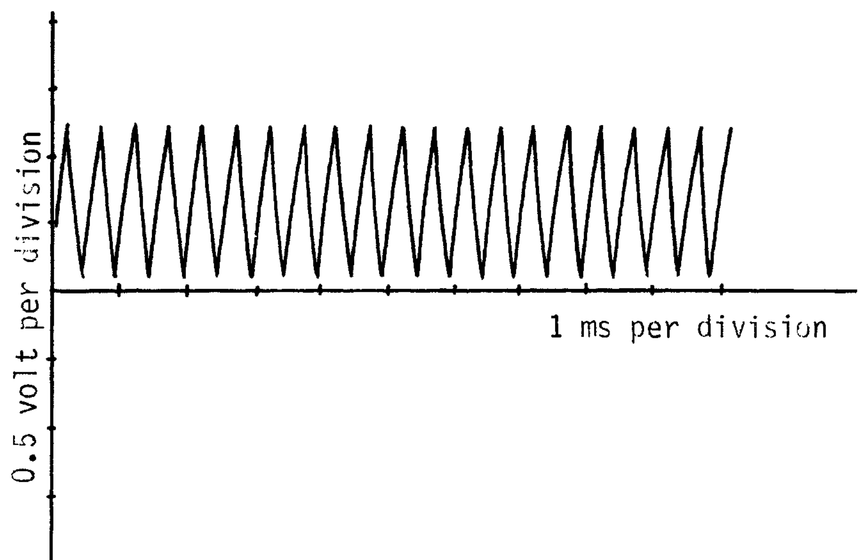
IV. RESULTS

The modifier circuit (figure 5, system 1 and system 4), has a 10 gain limiter, is limited within ±1 volt, has a 1000 gain integrator. When this circuit is being driven by a 1000 Hertz sine wave, the modified input, a, and feedback, b, are presented in figure 6. These two signal are compared and integrated in system 2 and the result (error r) is shown in figure 7. The maximum aplitude of error signal, r, shown is approximately 1 volt. The D.C. level to frequency convertor has the output (when integrator 6 has 1000 gain and the reference voltage is 10 volt) shown in figure 8.

The transient response to step frequency changes of zero to 1000 Hertz and zero to 1200 Hertz was recorded in figure 9. The time constant of this response is 3.5 milliseconds (appendix A). Standard frequencies from 300 to 1200 Hertz with 100 Hertz increments were obtained from a frequency generator. These were then applied to the input of the system and output was recorded with a digital voltmeter. The steady state operation relating output voltage to speed is shown in figure 10. The integrator in system 2 for these steady runs was set-up with a 4 volt initial condition and a 1000 gain on the input, the reference voltage (system 3) was set at three different values 13 volts, 10 volts and 7 volts and steady state curves produced for these different reference voltages. These curves were taken for input frequency above 300 Hertz because at frequency less than 300 Hertz the output tended to fluctuate.



modified input signal a



modified feedback signal b

Figure 6. Modified Signal (1000 Hertz Input)

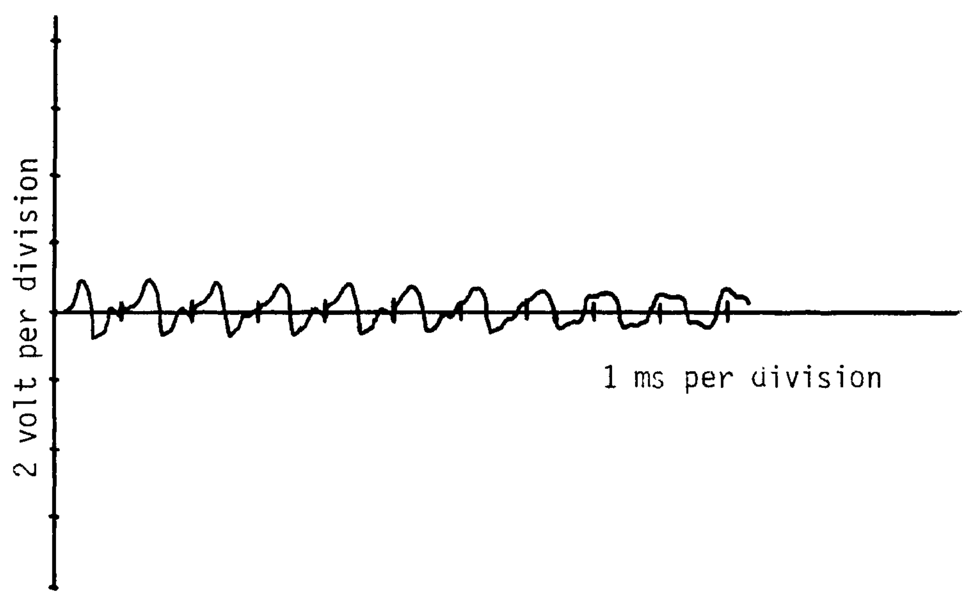


Figure 7. Error Signal (1000 Hertz Input)

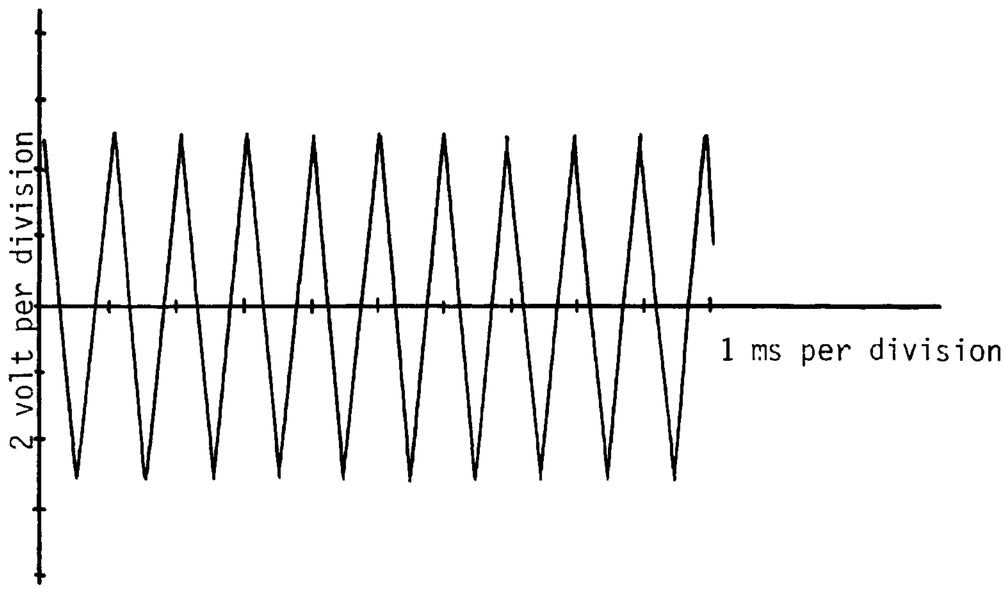
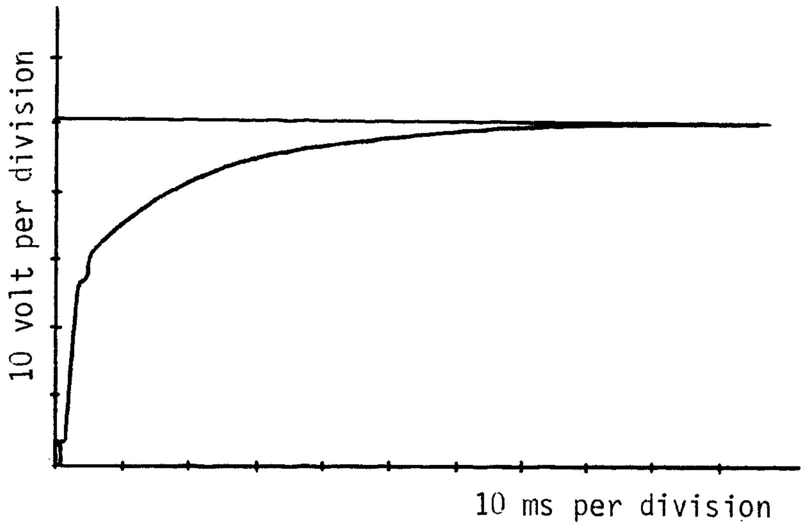
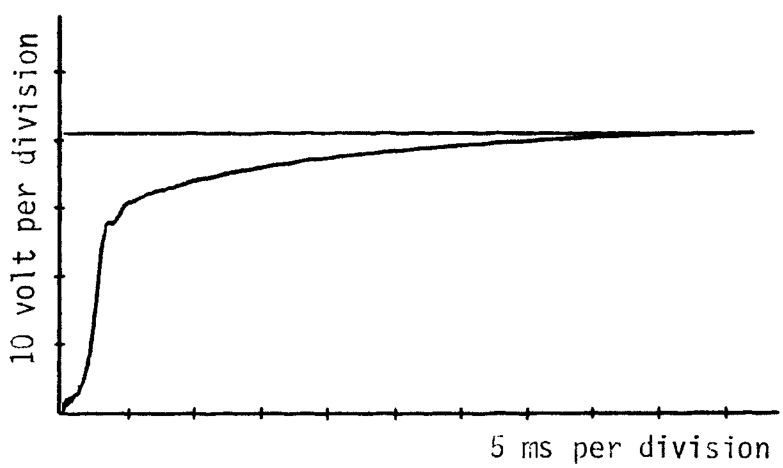


Figure 8. Output of D.C. Level to Frequency Convertor



1200 Hertz Input



1000 Hertz Input

Figure 9. Transient Response of Overall Measuring System

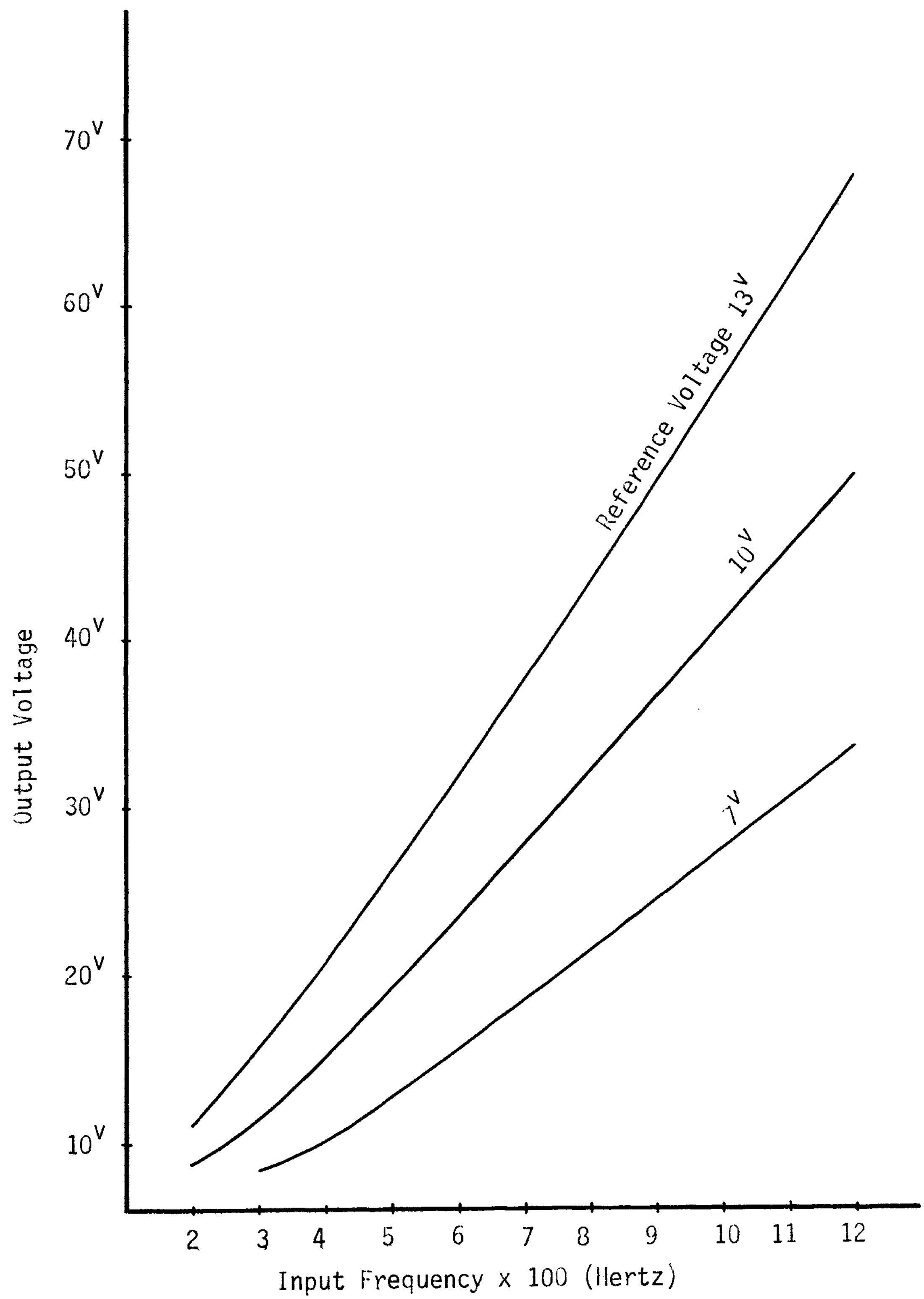


Figure 10. Steady State Response of Overall Measuring System

It must be pointed out that the 300 Hertz limitation is input frequency and not shaft speed. So if the shaft had multiple teeth, the speed could be quite low before measurement would be inaccurate.

If slower speeds were desirable to be measured, this could be accomplished by reducing the system gain.

V. CONCLUSION

The following conclusions were made about the system presented.

1. The system demonstrated good input frequency to output voltage linearity above 300 Hertz.

2. The response of the system to speed changes is rapid, demonstrating a time constant of 3.5 milliseconds.

3. The output of the system could be easily adapted for use with a speed control system.

4. The system has disadvantages of having to set reference voltages accurately and uses in large numbers, combinations of amplifiers, electronic switches and diodes.

5. The system also requires that an initial condition mode be provided in order to insure proper start-up.

6. The combination of statements 4 and 5 makes the fabrication of a black box transducer difficult and expensive.

BIBLIOGRAPHY

1. Perrson, D. L., The Development and Analysis of a System to Measure Transient Angular Velocity. Thesis, University of Missouri-Rolla, 1970.

2. Sauant, C. J. Jr., Basic Feedback Control System Design. McGraw Hill Book Company, Inc., 1958.

3. Kuo, Tsung-I., Automatic Control System. Prentice-Hall, Inc. 1964.

4. Hannauer, G., Basics of Parallel Hybrid Computers. Electronic Associates, Inc. 1968.

VITA

Tung-Ming Huang was born on June 22, 1944, in Miao-Li, Taiwan, Republic of China.

He received his primary education in Miao-Li, and his secondary education in Taipei and Hsin-Chu, Taiwan. He received his Bachelor of Science Degree in Mechanical Engineering from Chung Yuan College of Science and Engineering, Tao-Yuan, Taiwan, in June 1968.

In September 1970, he entered the Graduate School of the University of Missouri-Rolla.

APPENDICES

APPENDIX A

TIME CONSTANT

The time constant of the measuring system can be determined from the picture (figure 9) by the time at which the curve reaches 63.2% of its final value.

Time constant determination for the step input of

a) zero to 1000 Hertz

0.6 division x 5 millisecond per division = 3 milliseconds

b) zero to 1200 Hertz

0.4 division x 10 millisecond per division = 4 milliseconds

The average of the two step frequency change is 3.5 milliseconds.

APPENDIX B

TEST DATA FOR SYSTEM CALIBRATION CURVE

The input frequency was applied to the input of figure 5. The output was recorded from a digital voltmeter. The reference voltage (system 3) was set at three different values:

A. Reference voltage = 13 volts

Input Frequency (Hertz)	Output (volts)
1200	68.2
1100	61.9
1000	55.7
900	49.6
800	43.6
700	37.7
600	31.9
500	26.3
400	20.8
300	15.4
200	10.9

B. Reference voltage = 10 volts

Input Frequency (Hertz)	Output (volts)
1200	50.0
1100	45.2
1000	40.8
900	36.4
800	32.0
700	27.6
600	23.3
500	19.3
400	15.3
300	11.3
200	8.6

C. Reference voltage = 7 volts

Input Frequency (Hertz)	Output (volts)
1200	33.6
1100	30.6
1000	27.5
900	24.4
800	21.4
700	18.5
600	15.6
500	12.8
400	10.1
300	8.5
200	---