AN ELECTRONIC AIRSPEED INDICATOR OF HIGH PRECISION

by

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INTRODUCTION

The purpose of this thesis is to describe the theory and development of an Electronic Airspeed Indicator. This research project was undertaken as part of Project 169 of the Engineering Experiment Station, Kansas State College. Project 169 is a research project dealing with the measurement of airspeed and temperatures throughout a room being heated by a central overhead forced-air duct.

The requirements established for the Electronic Airspeed Indicator were

Airspeed range: Up to 50 feet per second
Temperature range: Up to 250° F.
Accuracy: 0.4% of full scale

Airspeed may be measured in many ways. Ordinary measurements in aircraft are made by means of a pitot tube which converts dynamic air to an equivalent static air pressure. This air pressure is fed to a closed container having one flexible side in the form of a thin disc, the opposite side of which is exposed to atmospheric pressure, the design being similar to the aneroid barometer. A suitable linkage operates a pointer on a calibrated scale giving direct readings in miles per hour as a function of diaphragm displacement. Such a mechanism is subject to a number of errors. These are (1) play in the mechanical linkage, (2) air temperature variations, (3) temperature effects on the mechanism, and (4) changes in the static air pressure. Such devices are inaccurate at low airspeeds.

Another airspeed measuring system makes use of the direct measurement of the difference between the static and dynamic air pressures by means of a sensitive scale balance, the presures being applied in an inverted chamber sealed in oil. A direct reading in milligrams is obtained. This must be converted to airspeed value. The system has inherently a short-time constant which makes it subject to minor variations in air pressure. Temperature corrections must be made for the temperature of the airstream being measured. Several minutes are usually required to obtain a reading. This system has the advantage of being simple and compact. The scale balance system has been used for the past few years for airspeed measurements on Engineering Experiment Station Project 169. The shortcoming of this system and the desirability of having a device adaptable to automatic recording of the airspeed led to the development of an Electronic Airspeed Indicator.

Two other systems of airspeed measurement for low airspeeds include (1) a pulsed ionizing arc upstream from a suitable ion detector, and (2) a device using the cooling effect on a thermistor as a measure of the stream air speed. The first system is not readily adaptable to automatic recording, and therefore was not considered. The second system would be directly affected by the variable airstream temperature and was therefore not considered because of the additional complication introduced.

THEORY OF THE ELECTRONIC AIRSPEED INDICATOR

The Electronic Airspeed Indicator operates on the principle of heterodyning oscillators. This principle has been used in electronic instruments for a number of years. One such device was used to test the moisture content of wheat and other grains. The amount of moisture in the grain, as compared to a standard sample, would change the dielectric constant of a condenser, and thus its capacitance. The change of capacitance caused the frequency of a vacuum-tube oscillator to deviate from the reference value and a beat note resulted from the mixer tube. The mixer tube was fed a reference signal and the resulting beat note was the difference between the fixed and the variable input signals.

Air velocity was measured in this system by first converting it to an equivalent static head with a pitot tube projected into the air stream. Air was taken from the pitot tube at a static pressure proportional to the square of the velocity of the impinging air. This pressure was applied to one side of a thin, stretched diaphragm of 0.001 inch thick aluminum foil. Static air pressure from the elevation of the impact point was applied to the other side of the diaphragm. The resulting displacement of the diaphragm was a function of the differential pressure. This thin diaphragm functioned as one plate of a condenser which tuned an oscillator, thus determining its frequency. This frequency was fed to one grid of a pentagrid converter tube. A reference frequency was fed to the other signal grid of the converter tube and a beat-frequency difference appeared in the converter tube output.

The first approach to the problem of converting the intermediate result (frequency) to airspeed was to find a means of measuring the audio output frequency. An overall accuracy requirement of 0.4 per cent made it desirable that the accuracy of reading the beat frequency be 0.1 per cent. A search of the literature revealed that such a problem was a difficult one to solve. Commercially, an accuracy of one to two per cent is acceptable for frequency meters.

In an attempt to solve this problem in another manner, the null-balance method was devised. This system made use of a mechanically-driven precision condenser to remove from the variable oscillator grid-tank circuit exactly the same amount of capacitance that the static air pressure introduced. This brought the oscillators into synchronism and made the frequency output of the mixer tube go to zero. The advantage of this system was that the necessity for reading an audio output frequency precisely was eliminated. The reading could now be read in terms of the amount of capacitance introduced to restore balance.

The balancing system required two types of null indication. The first of these was an aural indicator consisting of an audio amplifier tube driving a loud-speaker. The response of the system went down to about 10 cycles per second. This audio output was necessary to tell the operator which way to turn the balancing condenser in order to restore null balance to the system. The operator needed to turn the condenser in a direction such as to reduce the audio beat frequency.

In order to take advantage of the inherent high reading precision of the system of better than one part per million, a visual null indicator was designed to operate simultaneously with the audio indicator. This indicator consisted of a 6E5 electron-ray tube. This tube was directly coupled to the load resistance of the mixer tube. The frequency response of this circuit extends to zero beat and can be read to one part in several million. For example, a condition where the reference oscillator was operated at exactly 1,000,000 cycles per second and the variable oscillator was operating at 1,000,000.1 cyclesper second would give a closing rate on the 6E5 of one cycle per 10 seconds. The 6E5 cannot be read at frequencies greater than the eye response rate; i.e., 20 to 30 cycles per second. The audio amplifier response extends down to 10 cycles per second, and therefore adequately overlaps the visual indicator range.

The accuracy of the overall system is dependent upon the accuracy of the various components. There are

1. Crystal oscillator stability
2. Variable oscillator stability
3. Reading accuracy

The crystal chosen was a 100-kilocycle reference crystal that was designed to be very stable with time and temperature. The crystal unit and circuit was originally used in the Loran aircraft navigation system. Zink reports that such crystals may be expected to have a long time stability of ±0.02 per cent without temperature control.[1] The effect of line voltage varia-

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[1] A. J. Zink, Jr., "Stability of Crystal Oscillators," Electronics, 20:127, May, 1947.

tions were reported to be one part per million for line voltage changes from 95 to 125 volts.

The variable oscillator is subject to the most variation since it is operated as a self-excited oscillator. This oscillator had to be easily tunable by the grid-tank condenser, yet stable with regard to voltage and temperature variations. The electron-coupled oscillator was chosen in preference to the Clapp oscillator because it responded more readily to grid-tank tuning.[1] Most mica condensers have a positive temperature coefficient but such standards do not appear on the condenser markings and are not accurately controlled in manufacture; therefore it was felt that the most efficient procedure would be to build the circuit and test it, using negative coefficient ceramic condensers as required for temperature compensation.

The reading accuracy should be several times better than the overall accuracy requirements of the system. This is discussed in detail in the section on circuit development.

While the components of the circuit were subject to appreciable long time variation with temperature, proper operating techniques made it possible to minimize errors. A system zeroing technique was devised with this in mind. First, the head assembly was operated inside a temperature-insulated box so that the temperature variation was slow. Second, the variable oscillator tube chosen was a 1A7/GT which had two advantages: (1) ease of regulation of both plate voltage and filament cur-

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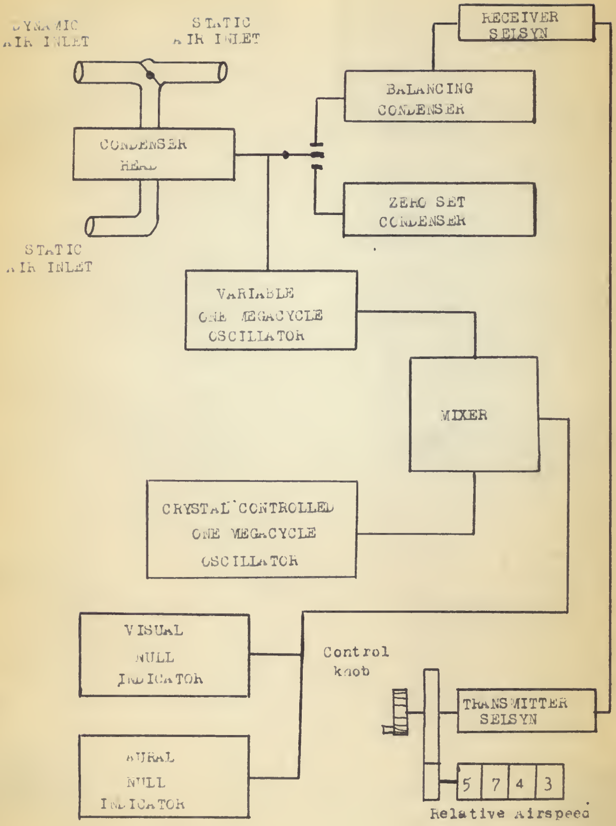
[1] J. K. Clapp, "An L-C Oscillator of Unusual Frequency Stability," Proceedings of the I. R. E., 36:356-358, March, 1948.

EXPLANATION OF PLATE I

Block diagram of the Electronic Airspeed Indicator

PLATE I


DYNAMIC AIR INLET
STATIC AIR INLET
RECEIVER SELSYN
BALANCING CONDENSER
CONDENSER HEAD
ZERO SET CONDENSER
STATIC AIR INLET
VARIABLE ONE MEGACYCLE OSCILLATOR
MIXER
CRYSTAL CONTROLLED ONE MEGACYCLE OSCILLATOR
VISUAL NULL INDICATOR
Control knob
TRANSMITTER SELSYN
AURAL NULL INDICATOR
5 7 4 3
Relative airspeed

EXPLANATION OF PLATE II

Photograph of the Electronic Airspeed Indicator system showing the pitot tube and head assembly at the upper center and the control panel at the right. The heated air duct is located at the ceiling and projects the air toward the floor. On the left of the operating table is the temperature indicator, at the center the scale balance used to measure airspeed and at the right the micromanometer used for calibration of the static head. The moving rack assembly permits the head assembly and pitot tube to be moved both vertically and horizontally.

PLATE II

rent, and (2) a low rate of heat generation. This was an advantage in maintaining a low temperature change rate in the head assembly. Third, a simple zeroing system in which the balancing condenser is switched out of the circuit by means of a relay, and a capacitance equivalent to the residual capacitance of the balancing condenser substituted. This made zero setting at any temperature very quick and eliminated the necessity of turning the balancing condenser back each time to the reference position. To establish reference pressure for the zero-setting operation, the existing atmospheric pressure was applied to both sides of the condenser head diaphragm by means of a remotely operated valve.

CIRCUIT DEVELOPMENT

The general organization of equipment was arranged in two major units, the head assembly which contained only the variable oscillator, condenser head and balancing condenser with its selsyn drive, and the master control panel consisting of three sections, power supply, reference oscillator, and null indicators with balance control. With this arrangement only the head assembly was subject to the high operating temperatures, and therefore required temperature compensation. Remote control, using two 57.5/57.5-volt, 400-cycle selsyns connected back-to-back on 24 volts, 60 cycles, was used to rotate the balancing condenser in the head assembly. A relay in the head assembly was used for zero-setting purposes.

EXPLANATION OF PLATE III

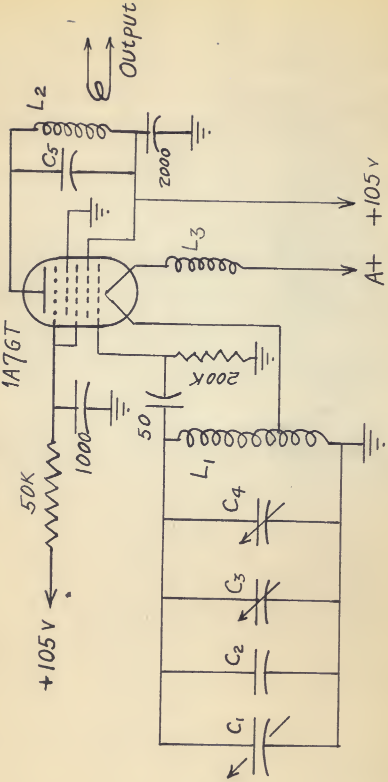
Schematic diagram of the variable oscillator

C_1 = pressure head

C_2 = 467-mmf mica

C_3 = 50-mmf ceramic
C_4 = 20-mmf air trimmer
C_5 = 421-mmf fixed mica and 100-mmf air trimmer

L_1 = 39 turns of No. 20 wire
1-1/4 inch O.D. tapped
7 turns from ground end
L_2 = 42 turns No. 20 wire
1-1/4 inch O.D.
L_3 = 2.5-mh RF choke


Output
L2
C5
2000
+105 v
L3
A+
1A7GT
200K
50
1000
50K
+105 V
L1
C4
C3
C2
C1

Variable Oscillator

Due to the frequency variation requirement of the variable oscillator, the electron-coupled oscillator was chosen in preference to the Clapp oscillator. In order that the rate of temperature change in the head chamber be kept to a minimum, a 1A7/GT pentagrid converter tube was chosen. The wattage dissipation of this tube was 70 milliwatts as compared with almost 2 watts for a 6SA7 tube. The 1A7/GT had the additional advantage that voltage regulator tubes could be used to regulate both the plate voltage and filament current. In order to minimize the number of tube types, the VR-105 voltage regulator tube was chosen for both functions although Zink states that voltage regulation of V-R tubes improves as the voltage rating is reduced.[1]

The circuit of the variable one-megacycle-per-second oscillator is essentially a Hartley oscillator in the oscillator section of the tube, electron-coupled to the plate circuit. To provide effective shielding between the oscillator circuit and the output circuit, both the suppressor grid and the unused insertion grid were grounded. The screen grid, which was effectively the plate of the triode oscillator circuit, was decoupled from the plate-supply voltage source. Mica and ceramic condensers were used throughout because of the temperature considerations.

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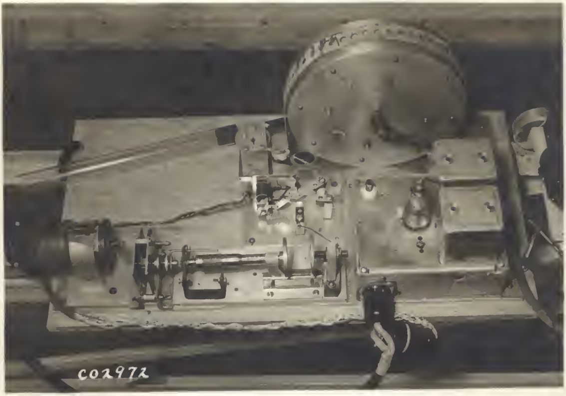
[1] Zink, <u>op. cit.</u>, p. 127.

EXPLANATION OF PLATE IV

Photograph of the head assembly.

PLATE IV



From the equation of a resonant circuit, $f_o = \frac{1}{2\sqrt{LC}}$, it can be seen that the smaller the total shunting capacity in the grid-tank circuit, the more sensitive the system becomes. The circuit was intentionally designed with a large C, however, because adequate sensitivity (frequency shift with pressure) could be obtained while leaving a relatively large C to permit the use of negative coefficient temperature compensating condensers. A further control of sensitivity was designed into the condenser head in the form of an adjustable spacing between the fixed plate and the moving diaphragm. The frequency stability of oscillator circuits depends in part on the Q of the resonant circuits. In this case a coil Q of 90 at 1 megacycle was used; while not being the highest possible, it was a satisfactory compromise with coil size.

The condenser head was designed with an outside diameter of 8 inches and an active back plate diameter of 5½ inches. The head consisted essentially of two sealed chambers divided by the 1-mil stretched diaphragm. The fixed back plate was supported about 1/10 inch from the diaphragm. A sealed insulating bushing was used to connect the fixed plate to the grid end of the grid-tank coil. A threaded ring turning inside the case adjusted the diaphragm tension.

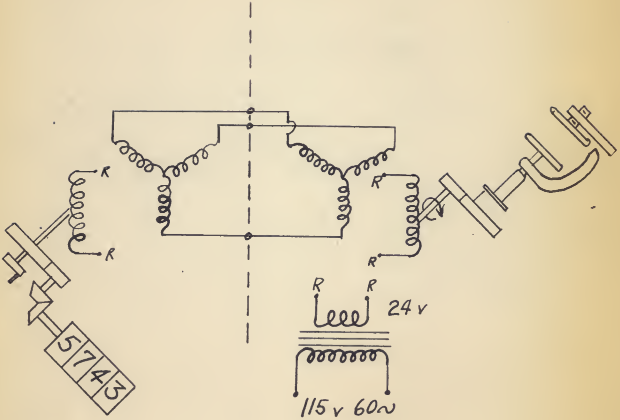
To minimize loading effects, a 2-turn pick-up loop was inserted in the plate-tank coil near the grounded end. This coil fed a low impedance line carrying the 1-megacycle-per-second signal from the portable head to the fixed mixer panel.

Associated with the condenser head and the variable oscillator inside the temperature shield is the balancing condenser. This unit was designed to have parallel plates driven from a

EXPLANATION OF PLATE V

Semischematic of balance drive.

PLATE V



modified micrometer. This permitted final adjustment of the total capacity change to be made by adjusting the position of the back plate while leaving the total screw travel (40 turns) unchanged. This was an advantage that the original concentric design did not have. An accuracy analysis of the selsyn drive system shows that on a 40-turn excursion basis, a 15-degree lag between the transmitter selsyn and the receiver selsyn was permissible. Actually, the final design had a 4x1 gear train introduced which made the permissible lag 60 degrees for a 0.1 per cent error. A semipictorial view of the selsyn drive system appears in Plate V.

The normal zero-setting procedure would require the application of the same pressure to both sides of the diaphragm and the setting of the balancing condenser to the minimum capacitance condition. The last step was eliminated by means of a switching relay in the head unit that switched in a reference capacitor of the same value as the residual capacitance of the balancing condenser.

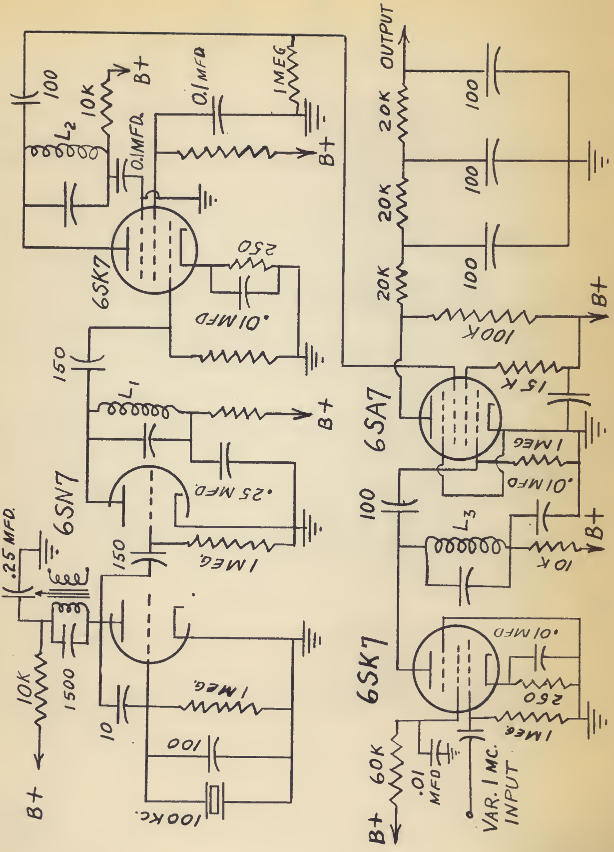
Crystal Oscillator

The crystal oscillator was designed using a standard 100-kilocycle-per-second high-stability crystal. The crystal was operated with one triode section of a 6SN7 dual-triode tube. The second triode section was operated as a quintupler giving an output of 500 kilocycles. This signal was fed into a 6SK7 pentode amplifier having the plate circuit tuned to 1 megacycle.

EXPLANATION OF PLATE VI

Schematic of crystal oscillator-mixer

PLATE VI



B+
10K
1500
.25 MFD.
10
100
100KC.
1 MEG.
150
6SN7
1 MEG.
.25 MFD.
L1
B+
150
.01 MFD
250
6SK7
0.1MFD
L2
10K
100
B+
0.1 MFD
1 MEG
B+
−
OUTPUT
20K
20K
20K
100
100
100
100K
B+
6SA7
15 K
1 MEG
.01 MFD
100
L3
10 K
B+
6SK7
.01 MFD
250
1 MEG
60K
B+
.01 MFD
VAR. 1 MC.
INPUT

Mixer

The mixer circuit was designed around a 6SA7 mixer tube operating into a 100,000-ohm resistance load. The first grid of the mixer tube was fed the variable oscillator signal and the second control grid was fed the reference oscillator signal. The resulting difference signal was developed across the plate load resistance.

Null Indication

Two null indicators were provided. First, a 6L6 was resistance-capacitance coupled to the output of the 6SA7 mixer tube. Since low frequency response was desired,a long-time-constant grid-coupling circuit of 0.1 microfarad and 1 megohm was used. This gave a time constant of 0.1 second which provided an adequate overlap between aural and visual null indicators. Since the ear is incapable of responding to zero frequency, a visual null indicator using a 6E5 electron-ray tube was used. The grid of the 6E5 was directly connected to the plate of the 6SA7 mixer tube. This design required a separate direct-current power supply of moderate voltage to permit the cathode of the 6E5 to be adjusted to a d-c level of +3 volts with respect to the grid. The plate supply and target of the 6E5 required a still higher voltage to cause the tube to operate properly. Proper use of the null indicators required that the operator adjust the balance control for the lowest audio frequency from the loud-speaker and then adjust for a stable open

EXPLANATION OF PLATE VII

Fig. 1. Aural null indicator.

Fig. 2. Visual null indicator.

PLATE VII

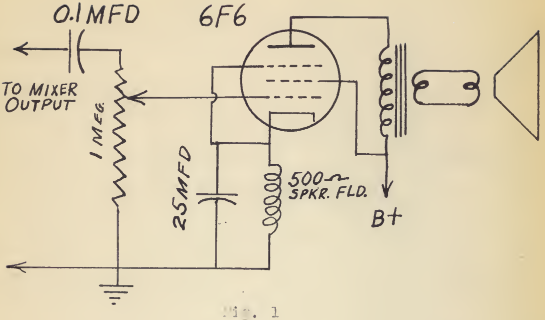


Fig. 1

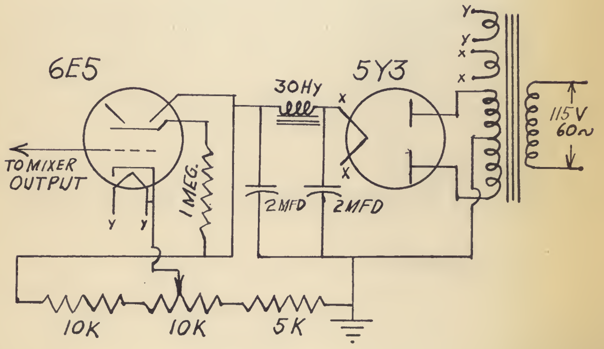


Fig. 2

or closed position of the 6E5 visual indicator.

Balancing System

The balancing system was designed using a knob extending from the lower panel of the master unit as a means of manually balancing the system to a null. This knob was connected to the driving selsyn directly. Manual adjustment of the knob to within a few degrees is quite feasible. A 60-degree knob displacement would result in an error of only 0.1 per cent. The output indication of the system consists of a Veeder-Root counter geared to the drive selsyn with a 5 to 1 ratio. This causes the counter ~~s~~shaft to rotate 800 revolutions for the complete range of the balancing condenser. Since the last dial has 10 divisions, this means that 0.1 per cent of the total deviation is represented by eight digits on the last dial. The counter has a total capacity of 9,999 of which only 8,000 is used.

Power Supplies

The master power supply is unregulated. It consists of a power transformer rated at 325 volts, 200 milliamperes. A 5U4 rectifier tube is used followed by a 2-section L-C filter of conventional design. A 20-milliampere bleeder resistor is used across the output condenser for improved regulation and safety. This unit supplies power for the entire system with the exception of the 6E5 electron-ray tube.

The 6E5 power supply has a requirement of high voltage and

EXPLANATION OF PLATE VIII

Fig. 1. Schematic of master power supply.

Fig. 2. Schematic of voltage regulator circuit.

PLATE VIII

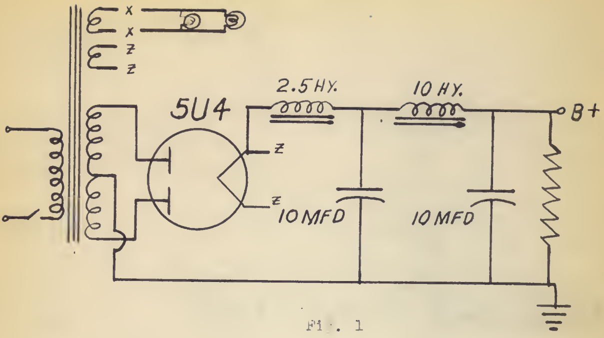


Fig. 1

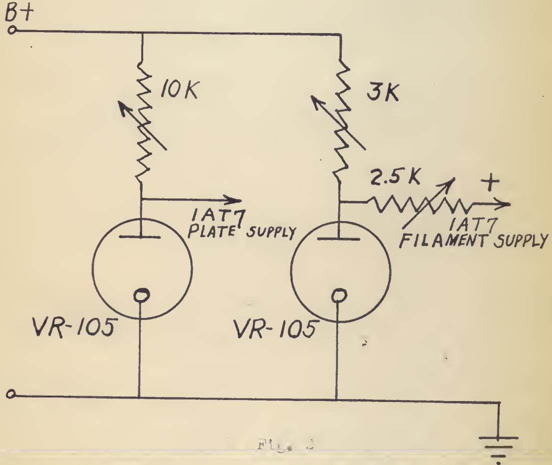


Fig. 2

low current. Since the drain is low and regulation presents no problem, a condenser input filter is used. The transformer used was of the small receiver type giving an output of 430 volts direct current.

A consideration was involved as to the operating conditions of the VR-105 regulator tubes during the warm-up period just after the power was turned on. A calculation of the worst condition encountered, that of no plate current drawn by all the heater type tubes, revealed that the plate regulator tube would be required to carry a current of only 25 milliamperes, while the filament regulator tube would have a momentary current of 40 milliamperes. This was within the rating of both tubes so no damage would result from such service.

TEST OF THE COMPLETED MODEL

Variable Oscillator

The variable oscillator was completed first and tested. The oscillator operated first as a blocked oscillator and gave spurious frequencies as picked up on a radio receiver. It was found that the time constant of the grid condenser-resistor was 17 microseconds. This was reduced to 8 microseconds and normal oscillations were obtained. This resulted in a pure beat note spaced at 1 megacycle on the BC-348 dial. Typical operation of the oscillator gave a plate tank voltage of 10 rms volts, a d-c grid voltage of -7 volts with respect to ground. The output of the pick-up loop was so low that it could only be estimated at approximately 0.1 volt. The circuit isolation was

EXPLANATION OF PLATE IX

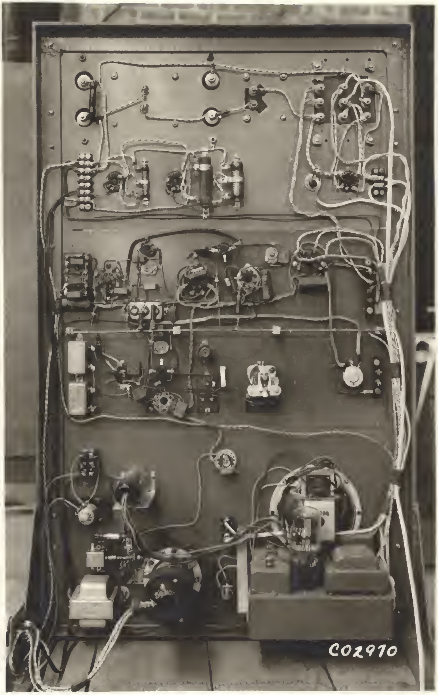
Photograph of the front of the control panel of the Electronic Airspeed Indicator.

PLATE IX

EXPLANATION OF PLATE X

Photograph of the rear of the control panel of the Electronic Airspeed Indicator.

PLATE X



tested by shorting the far end of the 1-megacycle line. No change in oscillator frequency resulted and this indicated adequate isolation. However, the oscillator frequency was affected somewhat by plate-tank tuning.

Reference Oscilator

The test of the 100-kilocycle reference crystal oscillator and the associated frequency multiplying circuits revealed spurious signals on the radio receiver. These were traced to a subharmonic mode suppressor connected directly across the crystal. The circuit was simultaneously operating at 33 kilocycles and 100 kilocycles. This was corrected by removing the series L-C mode suppressor circuit.

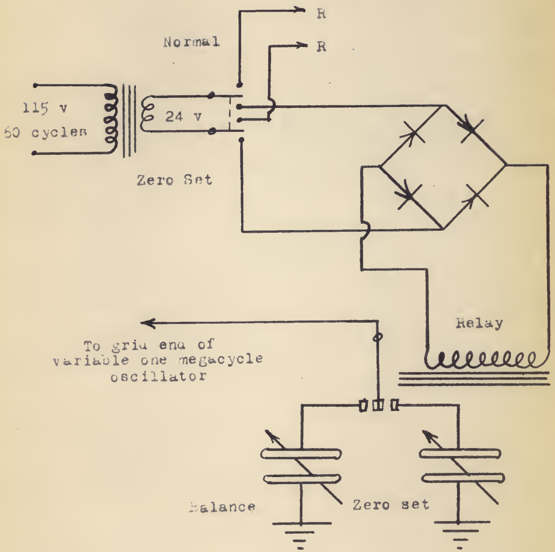
Mixer Panel

The mixer panel consisted of the 100-kilocycle crystal oscillator triode and circuits to multiply this frequency first by five and then by two to obtain the reference 1-megacycle signal. This output was measured at 40 volts to the third grid of the 6SA7 mixer tube. Tests revealed that the 0.1-volt output of the low impedance line coming from the variable 1-megacycle oscillator was too low to provide an adequate signal from the 6SA7 plate circuit to close the eye of the 6E5. To correct this, a 6SK7 radio-frequency amplifier tube was designed and mounted on the mixer panel. The circuit used an untuned input and a tuned output. A low Q-plate tank circuit was used to provide nearly uniform response for the 10-kilocycle deviation

EXPLANATION OF PLATE XI

Schematic diagram of the zero-set relay circuit.

PLATE XI


R
Normal
R
115 v
60 cycles
24 v
Zero Set
Relay
To grid end of variable one megacycle oscillator
Balance
Zero set

in frequency from the 1-megacycle oscillator. The variable 1-megacycle signal delivered to the first grid of the 6SA7 mixer tube by this circuit was measured at 5 volts. This input was adequate to close the eye of the 6E5 indicator tube.

Early tests on the mixer circuit using a cathode-ray oscilloscope to observe the beat-frequency output revealed high-frequency spurious signals in the plate circuit of the mixer. The magnitude of these signals was higher than the desired beat note and could not be accounted for by mixer theory that assumed pure sine-wave inputs.[1] Since the 1-megacycle signal to the third grid was obtained from a 100-kilocycle crystal source by means of frequency multipliers having low Q tank circuits, the reference input signal to the mixer was examined. The examination revealed the presence of prominent subharmonics.

The problem was solved by installing a resistance-capacitor ladder-type filter on the output of the mixer to discriminate against the spurious signals. Prior to this, series-tuned resonant filters were tried but were not satisfactory. These filters were simultaneously tuned to 1 megacycle and 2 megacycles. Coil Q's of 200 were used to obtain a low impedance at the desired pass frequency but the results were not satisfactory. The final design was arranged to give a 3-decibel attenuation at 100 kilocycles with a 20,000-ohm impedance per section. The source impedance for this filter was about 100,000 ohms. The three-section filter provided adequate dis-

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[1] Fredrick E. Terman, Radio Engineering, Third Edition (New York: McGraw-Hill), 1947, p. 532.

crimination against the high-frequency signals and minimum attenuation of the audio beat frequency. The mixer panel circuit appears in Plate VI.

A 6F6 audio amplifier tube was incorporated on the mixer panel to give an audible indication of the beat frequency. Adequate volume was obtained from the loud-speaker at all frequencies.

Power Supplies

The master power supply delivered 235 volts under the full load of 118 milliamperes. The hum level was too low to be measured on the oscilloscope and thus was considered sufficiently low. The VR-105 filament regulator tube was adjusted to give 50 milliamperes filament current to the 1A7/GT tube. The plate current of this VR-105 was adjusted to 20 milliamperes to assure adequate regulation range. The VR-105 plate-voltage regulator was adjusted to give a plate voltage of 105 volts to the 1A7/GT tube while drawing a plate current of 17 milliamperes. The plate current of the 1A7/GT was measured at 3.4 milliamperes.

The 6E5 power supply delivered a voltage of 430 volts with an rms ripple voltage of 11 volts under load. This gave satisfactory performance.

Balancing System

Tests of the first design of the condenser drive system did not give satisfactory performance. It was not possible to turn a threaded screw on a lathe to the tolerance required and still have a low enough drag to be driven by drive selsyn directly. The first screw built gave a 2.5 per cent change in maximum capacity of the balancing condenser due to play in the threads. Since the capacity of the balancing condenser was a measure of the airspeed,this would have meant too large an error in the overall result. A second screw was built and the threads were lapped in with lapping compound into the brass nut. This screw was too tight at a number of points for the selsyn to turn without excessive backlash. The third and successful attempt was made using a standard 1-inch micrometer. The micrometer was disassembled and cleaned in gasoline to remove the heavy grease. The tightening ring was removed to provide minimum drag and a light machine oil was used to lubricate the screw. To facilitate mounting of the moving section of the condenser, the condenser design was changed from the concentric cylindrical form to the parallel plate form. This allowed easier adjustment of the balancing condenser. The screw-mounted plate was used as the fixed plate and was thus adjustable while the fixed plate of the condenser assembly was fitted with a brass insert and set screw to permit mounting on the micrometer shaft. The parallel plate assembly was mechanically more rigid and required less overall length than the concentric cylinder assembly. The rate of change of capacitance versus dial reading for the concentric arrangement was linear,while for the parallel plate assembly the change of capacity for a given change in dial reading was less as the plates moved apart. The first tests of this assembly gave a backlash of about 0.1 per cent of the overall travel. This was considered excessive and was corrected by a 4x1 gear train allowing the selsyn to turn four revolutions as the micrometer screw turned one revolution. Thus while 15 degrees of rotational backlash between the selsyns was permissible before, the allowable backlash for 0.1 per cent error was now increased to 60 degrees. A test of the overall drive system gave a precision of one part in 8,000, or a following accuracy of 0.0125 per cent. This was considered adequate. The test was made by balancing the 6E5 eye to a null and reading the revolution counter dial, then rotating the dial off this setting several revolutions, then returning to null and again reading the dial. This was done for both directions of dial rotation. The 4x1 gear train now gave a selsyn rotation of 160 turns to drive the micrometer screw 40 turns and one inch of travel. This required 160 turns of the control knob and thus gave 800 of the counter dial. Thus in the final design the total balancing range was accomplished by a change of 8,000 in the dial reading.

Electrical Stability

The 1-megacycle crystal oscillator was compared with the United States Bureau of Standards radio station WWV. The frequency of WWV is kept accurate to one part in several million, and therefore served as a stable reference. The technique used was to feed the WWV signal from the antenna and the 1-megacycle

EXPLANATION OF PLATE XII

Fig. 1. A curve showing how the 1-megacycle crystal controlled reference frequency drifts with time.

Fig. 2. A curve showing the zero drift of the entire system with time. The system had been set to zero 20 hours before the start of this test.

PLATE XII

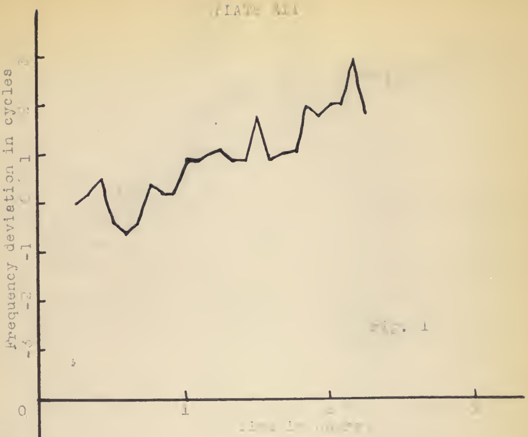

Fig. 1

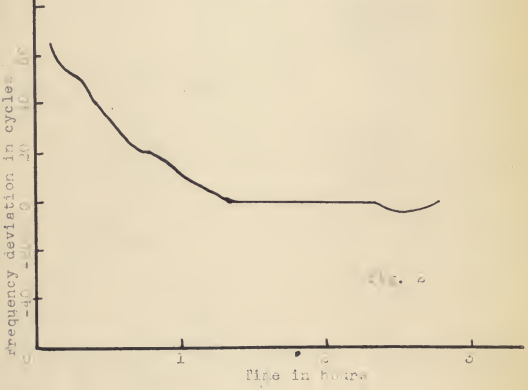

Fig. 2

signal simultaneously into the input of a radio receiver tuned to the 10-megacycle signal of WWV. The tenth harmonic of the 1-megacycle signal would then beat with the WWV 10-megacycle signal and the resultant audio note would appear at the receiver output. The frequency of this beat note was determined by applying it to the X-plates of an oscilloscope while applying a signal from an audio test oscillator to the Y-plates. The resulting Lissajous figures permitted the audio beat-frequency difference to be read on the calibrated dial of the audio oscillator.

A two-hour operating test from a cold start gave a total change of frequency of the 1-megacycle reference signal of 2.6 parts per million. During this time the audio oscillator was checked against the 440- and 600-cycle-per-second tone modulation on the WWV carrier by the Lissajous method and found to be very stable. Complete data are given in Plate XII.

In a line voltage variation test lasting 12 minutes, the line voltage was varied from 115 volts to 120 volts, down to 110 volts, and back to 115 volts. The maximum frequency deviation was 15 parts per million. It must be borne in mind that the stability of the overall system with line voltage variation is the important consideration. The components were tested to determine the contribution of each to the total deviation. The effect of a line voltage change on two oscillators should have a compensating effect and did have, as will be noted on the test of the entire system.

Warm-up stability tests on the entire system gave a change in output of 60 parts per million over a period of several

EXPLANATION OF PLATE XIII

Fig. 1. A curve showing the effects of line voltage variation on the stability of the system.

Fig. 2. A curve showing the results of temperature compensation experiments on the variable oscillator. The arrangement of condensers for this test was as follows:

Curve	A	B
Mica	467 mmf	484 mmf
Ceramic	50 mmf	33 mmf
Air trimmer	12 mmf	12 mmf

Curve A shows that over compensation for temperature is taking place, while curve B shows that under compensation is taking place.

PLATE VII

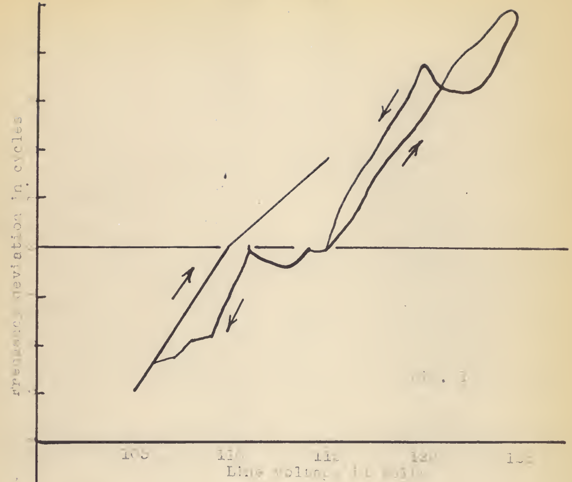

Fig. 1

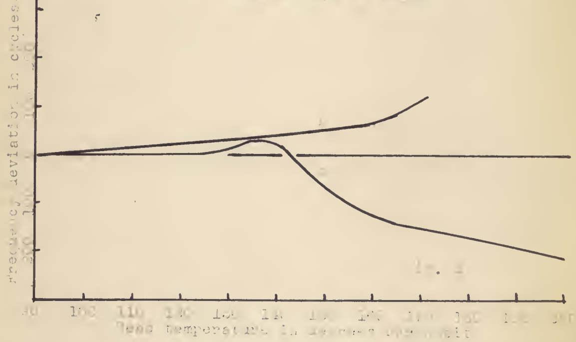

Fig. 2

hours. After the first 10 minutes of operation the change of beat was never more than 1 cycle per second (one part per million) for a 1-minute interval. Assuming a total frequency deviation of 10 kilocycles for the total range of airspeed measurement, this would mean an error of 0.1 per cent in reading over a time interval of 10 minutes. A quick and easy zero set procedure will effectively reduce this error to negligible magnitude. A voltage variation test on the entire system gave a variation of only 3.8 parts per million, or 0.038 per cent of the total airspeed range for line voltage deviations of 105 to 125 volts. These tests indicated that compensating effects were taking place in the oscillators.

Power consumption tests on the system gave an input current of 1.13 amperes at 115 volts, 60 cycles.

Zero Drift with Temperature

Temperature compensation of the variable oscillator proved to be a very difficult problem. Bushby indicates that a fixed frequency oscillator can be perfectly compensated for temperature by the use of proper temperature compensating components.[1] In this instance the oscillator frequency shift was only 1 per cent of the mean value, and therefore resembled closely a fixed oscillator. Fortunately, the system design was such that temperature drift of the oscillator did not affect the measuring

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[1] T. W. R. Bushby, "Therman Frequency-Drift Compensation," Proceedings of the I. R. E., 30:546, December, 1942.

accuracy since the system could be zero set and thereby synchronize the crystal oscillator with the variable oscillator at the existing temperature. It was desirable, however, to keep the temperature drift within the limits of the zero-set control and to keep the drift as low as possible to minimize the frequency of zero-setting operations. The problem was complicated by the lack of a sufficient range of capacitors with a known temperature coefficient. The grid circuit of the variable oscillator was compensated by the use of mica condensers of unknown positive coefficient and ceramic capacitors of 750 parts per million per degree centigrade negative coefficient. The circuit at hand seemed the most accurate means of evaluating the results since the compensation was really for the entire circuit, including the capacitor head. The technique used was to place the head assembly inside an insulating chamber about 16 inches square and 2 feet long and to control the voltage to two 250-watt strip heaters by means of a variable auto transformer as a means of regulating the temperature. As the temperature was increased inside the chamber as recorded by a thermometer bulb directly above the coil cans on the variable oscillator, the deviation in frequency of the variable oscillator with respect to the reference oscillator was measured and recorded. The technique here was to use an audio oscillator and oscilloscope and the Lissajous pattern as a means of determining the resulting audio beat frequency. About 20 runs were made, each requiring from 2 to 4 hours. An analysis of the data to determine the correct combination of mica and ceramic condensers failed because of the unknown value, and possibly a variable one, of the temperature coefficient of the mica condensers. Results of the two best temperature compensation runs appear in Plate XIII, Fig. 2. Since the range of the zero-set control on the reference oscillator is only 280 cycles per second, it can be seen that curve A will give satisfactory results if the system is zeroed at 100 cycles below the reference oscillator at room temperature.

Temperature Effects on Accuracy

Temperature effects on accuracy were determined by calibrating the equipment at room temperature and repeating the calibration with the head assembly in the temperature chamber. The problem encountered here was that small disturbances in atmospheric pressure caused continual fluctuations of the beat frequency making manual balance difficult. The calibration method first tried was the use of a small water column; however, this proved unsatisfactory because of slow leaks in the pressure side of the condenser head. It was discovered that the 1-mil thick aluminum foil (the ordinary kitchen variety) had minute pin holes in it. In operation this slow leak will not affect the accuracy but it did create a problem during static calibration. This problem was solved by including in the pressure system a large air storage head to supply the leakage losses. This was accomplished by using a 5-gallon jug with a reserve water head exposed to atmosphere in a 1-gallon jug. Three hoses entered the large jug--one to build up the pressure head by blowing, a second to apply the pressure

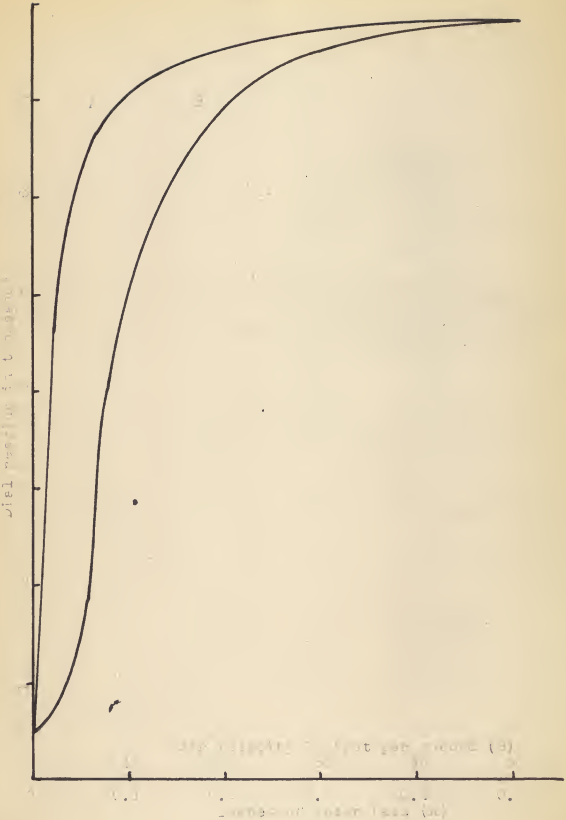
EXPLANATION OF PLATE XIV

Curve A shows the relationship between the calibration pressure head in inches of water and the resulting dial reading in thousands when the null indicators are brought into balance.

Curve B shows the equivalent air velocity in feet per second for standard conditions of barometer 29 inches, temperature 82 degrees F., and the resulting dial reading for the balanced condition. The equation relating velocity in feet per second and equivalent water pressure head in inches of water is:

$$V = 15.88\sqrt{\frac{542\,h}{29}}$$

L. XI



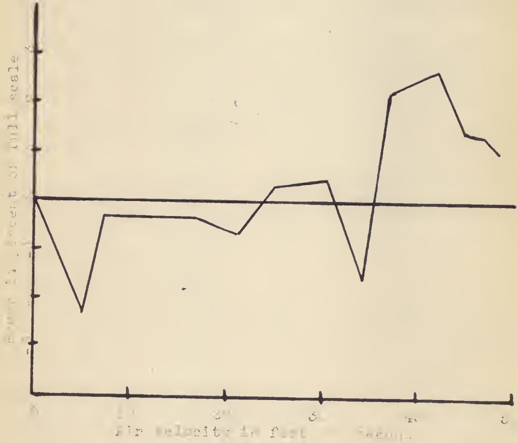
to the condenser head, and a third connecting to the water source at atmospheric pressure.

The approximate water head was established by blowing air into the large jug until the water level dropped approximately one-half inch below that of the small jug. The reference used for all measurements was a Merriam Instrument Company micromanometer, a water level indicating instrument calibrated to units of 0.001 inch of water. On the basis of 1/2-inch measurement capacity of the system, this would be 1 part in 500, where 1 part in 1000 was desired. Actually, the reading accuracy of the micromanometer was only about 0.003 inch, causing its accuracy to be 0.6 per cent of the measurement capacity of the Electronic Airspeed Indicator. Atmospheric disturbances such as doors being opened in the building would be instantly apparent by the development of a beat note. This coupled with a long time constant oscillation in the water level system and a back pressure developed by each adjustment of the micromanometer, made accurate calibration difficult. Plate XV shows that in the range of air velocities from 8 to 30 feet per second, the system repeats room temperature calibration to within 0.7 per cent under the 170-degree F. temperature condition. It is believed that improved calibration techniques and better control of the pressure would reveal much better system performance than was recorded here. It is important to note that the system returned to zero after the pressure was applied and then removed, indicating that no hysteresis occurred in the diaphragm. The deviation of up to 2.7

EXPLANATION OF PLATE XV

A plot of the error in the system for the same dial reading for static conditions and under a temperature of 170 degrees F. at the head assembly as compared with a previous static calibration at 82 degrees F.

PLATE XV


Error in percent of full scale
0
10
20
30
40
50
Air velocity in feet per second

per cent at the ends of the range is attributable to the scale factor of the dial system. This is indicated on Plate XV. Here it will be observed that at the high velocity the dial reading changed very slowly, making large errors possible. At a 33-foot-per-second air velocity, 0.1 per cent is represented by 1.46 dial divisions. The dial adjustment, especially under the calibration conditions imposed, became critical. At a low velocity of 7.5 feet per second, the 0.1 per cent of maximum measuring capacity is represented by 27.4 dial divisions; here, however, the 0.6 per cent reading accuracy of the micromanometer becomes predominant in determining the calibration error.

It should be noted in passing that on one temperature run up to 250 degrees F., the plastic shield on the balancing condenser drive selsyn melted; otherwise, no permanent damage was noted. Temperature measurements on the heated airstream tests indicated that the head would not be subject to temperatures exceeding 150 degrees F.; therefore, the temperature of 170 degrees F. was used for testing the Electronic Airspeed Indicator.

Dynamic Performance

While the system performed fairly well on static test, the manual balancing system could not be operated rapidly enough to cope with the rapid and large air velocity fluctuations encountered in the air stream. These variations would cause abrupt beat frequencies of the order of 1 kilocycle, or 1/10 of the range. The approximation of the deviation had not been possible with previous measurement methods. The first solution to the problem was the introduction of a long time constant in the pressure system supplying the condenser head. A 2- to 3-second time constant had been previously used in the form of a pin hole in the pipe plug fitting into the pressure side of the condenser head. In addition, a large bottle and needle valve assembly was inserted between the condenser head and the pitot tube. This did not improve the operation. Later analysis proved that to enable adequate smoothing of the pressure to within 0.1 per cent and assuming 1 second balance time, a time constant of 15 minutes would be required. This would mean a 15-minute wait between readings for the system to settle down. In a random system such as this, slow variations might introduce further complications.

FUTURE DEVELOPMENT

In view of the experimental data obtained with the Electronic Airspeed Indicator, it would appear promising to investigate the possibility of experimenting with a direct frequency measuring system to measure accurately the beat frequency as originally envisioned and described in the early pages of this thesis. One possibility is a frequency meter that would operate over the deviation frequency range of 0 to 10,000 cycles per second. Such an instrument should be a recording instrument. It is believed that no such commercial instrument exists. The most promising possibility seems to be the binary scaler such as is used in nuclear physics. This instrument could be gated from the 100-kilocycle crystal or an internal timing

EXPLANATION OF PLATE XVI

Data showing the cable wiring arrangement for the 75-foot connecting cable from the control panel to the head assembly.

PLATE XVI

CABLE DETAILS

Octal pin No.	Function	Color	4-pin socket	6-pin socket
1	Gnd, B-, A-, 1-mc ret., R_1, S_3, 24-v a-c ret., relay return	Black		1
2	A+ 50 ma	White		6
3	B- 105 volts	Red		2
4	R_2 (a-c high)	Blue	1	
5	S_1	White	2	
6	S_2	White	3	
7	Relay	White	4	
8	1 megacycle high	Green		4
	Spare			
	Spare			

source for an accurately timed interval. The output would be recorded in the form of accurately counted cycles. These devices count accurately to the last cycle,and therefore would have a recording accuracy commensurate with the basic system. Such a system would be a true integrating system and could be made to have an automatic recording feature.

Insofar as a static pressure measuring device is concerned, a nearly linear dial factor could be obtained by designing a balancing condenser in the form of a piston entering a truncated cone from the small end. Such a condenser would have the characteristic of a rapidly increasing capacitance at first and a slowly increasing capacitance at the end of the range at maximum air velocity. Such a unit could be designed by mechanical integration methods from experimental data on the existing system.

CONCLUSIONS

The Electronic Airspeed Indicator designed gave good performance from the standpoint of circuit stability and static performance but did not meet the overall performance requirements below about 10-feet-per-second and above 30-feet-per-second airstream velocity. Part of the error is attributable to the calibrating pressure fluctuations and to the micromanometer reference used. Temperature compensation of the variable oscillator was difficult with the components available but with more experimentation could probably be adjusted quite accurately. Uneven heating of the various head assembly components must be considered and may make necessary the enclosing of the head assembly in a heat-insulating box to assure an even temperature rise in all components. It is believed that the addition of a frequency-measuring system of an integrating nature, such as the binary scaler, would result in an ideal airspeed measuring system for these random conditions and that such a system would readily lend itself to automatic recording of the result.

ACKNOWLEDGMENTS

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AN ELECTRONIC AIRSPEED INDICATOR OF HIGH PRECISION

by

OLIVER VIRGIL RILEY

B. S., Kansas State College
of Agriculture and Applied Science, 1942

AN ABSTRACT OF A THESIS

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requirements for the degree

MASTER OF SCIENCE

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KANSAS STATE COLLEGE
OF AGRICULTURE AND APPLIED SCIENCE

1951

PURPOSE

The Electronic Airspeed Indicator was developed for the Engineering Experiment Station, Kansas State College, under Project 169. The purpose of the development was to provide a research tool superior to those now being used. One airspeed measuring method in current use measures the resulting pressure from a pitot tube by means of a scale balance, another method measures the pressure by means of a sensitive liquid level. Neither of these methods is automatic nor can the results be automatically recorded. One of the aims of this development was to design equipment that would adapt to automatic recording of the result.

GENERAL METHOD

The general method used was the development of circuits using a precision 100-kilocycle-per-second crystal oscillator circuit, the output of which was multiplied to a reference frequency of one megacycle per second. As electron-coupled oscillator operating at a frequency of one megacycle per second was tuned by means of a pressure-actuated capacitor, the pressure being obtained from a pitot tube in the air stream. The null balance principle was used in which the circuit capacitance varied by the air pressure was balanced with a selsyn-micrometer-driven balancing condenser to return the oscillators to synchronism. Both aural and visual null indicators were used.

PRINCIPAL RESULTS OBTAINED

The equipment resulting from this development consisted of two major parts, the master control panel measuring about 30 inches high and 19 inches wide, and the head assembly measuring 14 inches wide, 22 inches long, and 10 inches high. The master control panel contained power supplies, reference oscillator, radio-frequency amplifiers, mixer circuit, null indicators, and balance control. The head assembly contained the pressure-actuated capacitor, a variable oscillator, and a balancing drive. The head assembly was connected to the master control panel by 75 feet of eight-conductor cable. This permitted the head assembly to operate in the air stream near the pitot tube.

The design objectives were:

Airspeed range: up to 50 feet per second

Temperature range: up to 250 degrees F.

Accuracy: 0.4 per cent of full scale.

Under static performance conditions the equipment gave errors of as much as 2.7 per cent at the high velocity range and at a temperature of 170 degrees F. Part of these errors were chargeable to the micromanometer used as the calibration standard, part to the change of dial sensitivity with velocity, and part to the random air pressure variations which affected the sensitive system. The system was never compensated for temperature but the zero-setting technique made this unnecessary. The system gave no error chargeable to hysteresis of the pressure diaphragm.

The dynamic air velocity conditions imposed on the system in actual use proved the manual balancing system to be far too slow in response. It is proposed that a binary or decade type of integrating-frequency recorder be used on the system. Mechanical air pressure integrating systems failed to provide satisfactory performance under the random air velocity conditions imposed.