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DEVELOPMENT OF A FREQUENCY-TO-VOLTAGE CONVERTER FOR SPACECRAFT INSTRUMENTATION SYSTEMS

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PART 1 - INTRODUCTION

The purpose of this document is to present a discussion of the development of a frequency-to-voltage converter, Engineered Magnetics Model EMSE-125, and to give a detailed description of its circuitry and operation. Using standard components, this unit combines small size, light weight, and low power consumption with excellent stability, linearity, and low noise under extreme environmental conditions. This unit is presently being used in Apollo/Lunar Module Spacecraft Instrumentation Systems.

1. DESCRIPTION

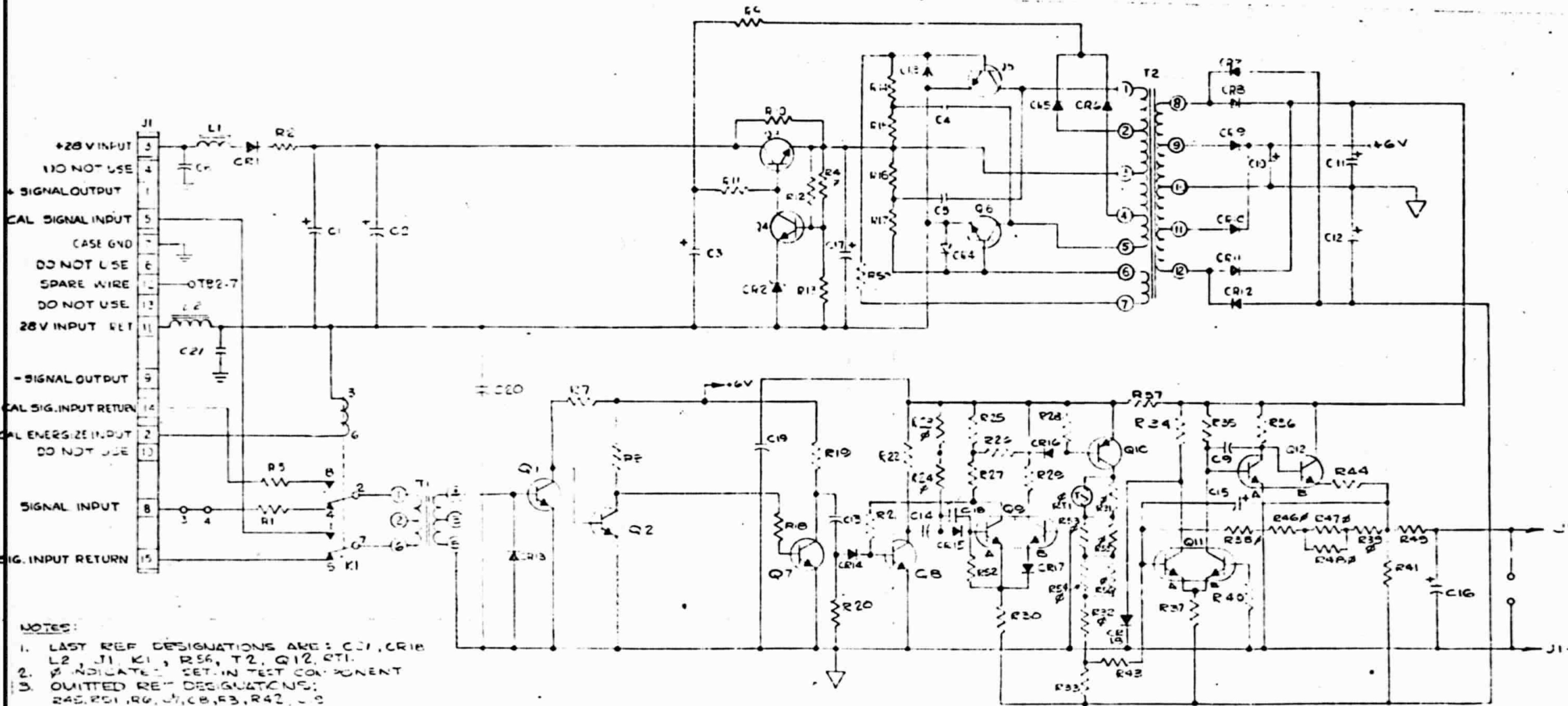
The Model EMSE-125 is a miniature frequency-to-voltage converter of conventional-component, welded-module construction. It is contained in a 6.3 cubic inch case.

This unit was developed under NASA supervision by Gulton Industries, Engineered Magnetics Division, under NASA Contract NAS 9-2524. Evaluated by the Instrumentation and Electronic Systems Division of the Manned Spacecraft Center (MSC), it meets the performance specifications as listed in Table 1 and the environmental specifications (based on Environmental Specification IESD 19-1B developed by MSC), contained in Appendix A of this document.

A schematic diagram of this unit is shown in Figure 1.

TABLE 1. SPECIFICATIONS OF THE EMSE-125 FREQUENCY TO VOLTAGE CONVERTER

Input supply voltage:	28 VDC nominal (24 to 32 VDC).
Input supply ripple:	4 V p-p maximum (dc to 2 KHz square wave).
Input transient:	±15 V, 20 msec base width, 8 msec rise time.
Feedback to input supply:	30 MV p-p maximum with source impedance 1 ohm.
Input supply polarity reversal:	Unit internally protected.
Input supply under-voltage:	To 22 VDC with 10% maximum degraded unit performance.
Input signal:	20 to 30 volts rms, 380 to 420 Hz or 760 to 840 Hz.
Input impedance:	50,000 ohms or greater for any frequency in the specified range.
Output signal:	0 to +5 volts.
Output impedance:	1000 ohms or less.
Output signal ripple:	25 MV p-p, dc to 15 MHz.
Warmup time:	15 minutes maximum.
Linearity:	±12.5 MV of a straight line between 0 (380 or 760 Hz) and +5 volts (420 or 840 Hz).
Conversion gain stability:	±125 MV.
Power consumption:	50 ma maximum with DC input supply voltage.
Common mode rejection:	100 db or more for balanced or unbalanced input lines (400 ohms maximum resistance) for frequencies from dc to 1000 Hz and voltages of +5 to -5 volts.
Weight:	6.5 ounces maximum.
Volume:	6.3 cubic inches



NOTES:

1. LAST REF DESIGNATIONS ARE: C21, CR18, L2, J1, K1, R56, T2, Q12, RT1.
2. Ø INDICATES SET IN TEST COMPONENT
3. OUITTED REF DESIGNATIONS: R45, R51, R6, J?, C8, R3, R42, [illegible]

Figure 1. Frequency To Voltage Converter

2. GENERAL

The Development Flight Instrumentation Systems for the LM program was allotted a minimum of weight, power and volume when compared to the numbers and characteristics of the measurements required to be transmitted.

Many components used on previous programs did not meet the requirements of the LM program because of their size, weight, power and environmental limitations. The frequency-to-voltage converter fell into this category thus making it necessary to completely redesign this component.

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PART 2 - FREQUENCY-TO-VOLTAGE CONVERTER

1. GENERAL

The Model EMSE-125 frequency-to-voltage converter is designed to produce a 0- to +5-VDC output linearity related to the frequency of the input signal (between 380 and 420 Hz, or between 760 and 840 Hz). Figure 2 shows a block diagram of the unit. A series regulator through a DC-DC converter provides isolated DC power and, with an inductance-capacitance (L-C) input filter, isolates the signal-conditioning circuitry from susceptibility to audio voltages impressed on the power section. Another L-C filter eliminates radio frequencies impressed on both input power leads.

The heart of the EMSE-125 is the stable one-shot multivibrator. This multivibrator produces a pulse of stable amplitude and duration, the repetition rate of which is locked to the frequency of the AC input signal. When the frequency is increased, the pulses occur more frequently, causing the DC level of the multivibrator pulses to change polarity and to approach the pulse peaks.

After the pulse is generated, an integrating amplifier removes the large "ripple" component, increases the voltage change to the desired value, and provides a low-output impedance. The input waveform, "squared" by a three-stage amplifier, then triggers the multivibrator.

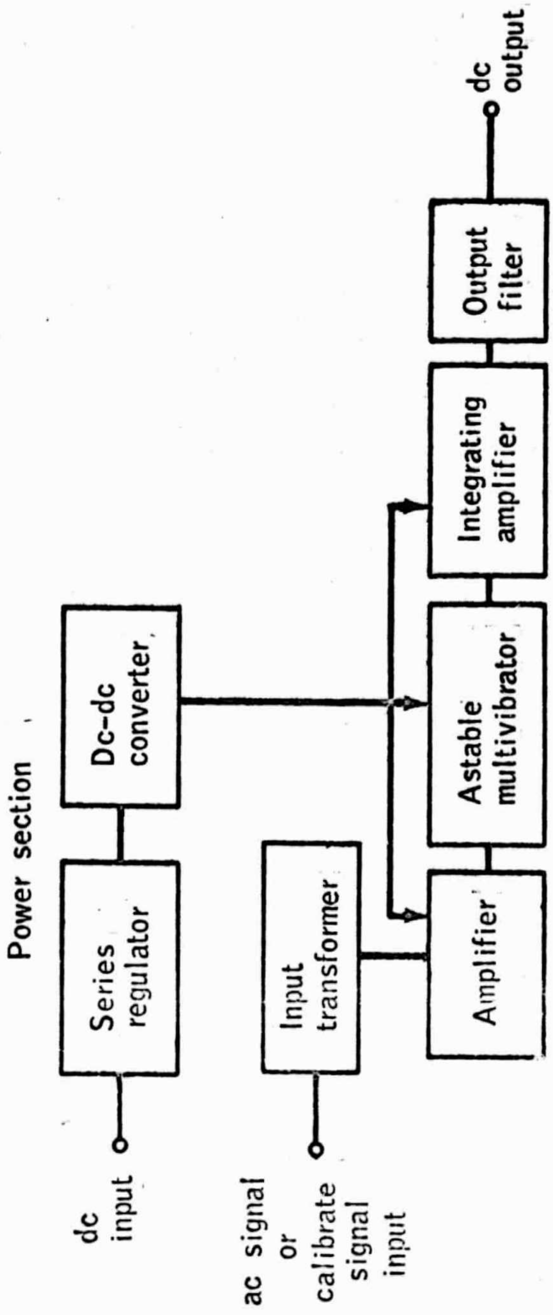


Figure 2. Frequency To Voltage Converter Section

The multivibrator is designed to ignore alternate sync pulses when the input frequency is in the "high" frequency range. To accomplish this, it is only necessary to set the duration of the astable state slightly greater than 1/760 second. For pulse rates of 380 to 420 Hz, each sync pulse starts a cycle of the multivibrator. For pulse rates of 760 to 840 Hz, the maximum sync pulse spacing is 1/760 second, thus, one sync pulse occurs while the multivibrator is in its astable state. Because the multivibrator is in the astable state, the incoming pulse has no effect on the multivibrator.

An input transformer provides DC isolation. Upon remote command, an internal "calibrate" relay connects the input transformer to an external frequency standard for function verification.

2. DESIGN AND DESIGN PROBLEMS

The unit input circuit operates at a high voltage level. The input transformer is used as a current transformer to maintain small size. The chief component of the input impedance is series resistance added in the primary circuit. The "squaring" or overdriven amplifier is a direct-coupled design.

Generating a multivibrator pulse with stable average value presented a design problem. Referring to the simplified schematic of the multivibrator, Figure 3, the stability of the output pulse (E_o) is affected by all the components designated with a circuit symbol.

2.1 Multivibrator Stable State

In the multivibrator stable state, Q2 is conducting (saturated) because of the base current through R1 and CR1. The collector current of Q2 flows partially to the base of Q4, saturating Q4. Component Q1 is cut off and, in this state, E_o is affected by an appreciable change in Q4

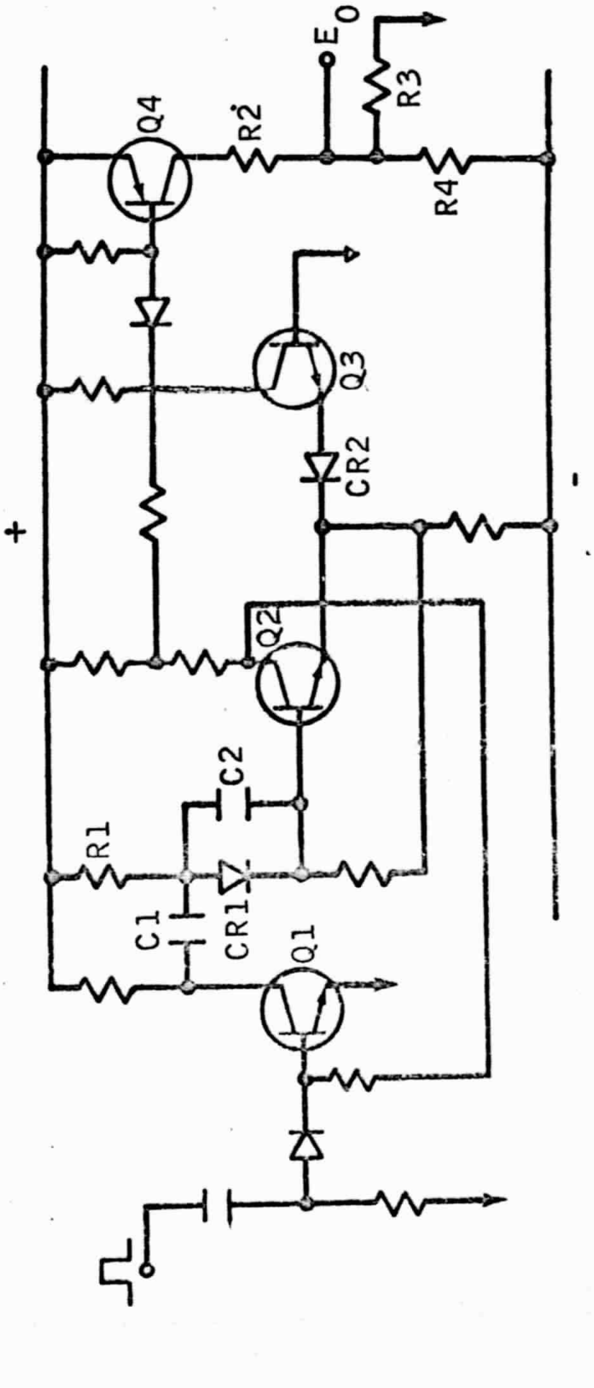


Figure 3. Simplified Schematic of Multivibrator

collector-saturation voltage or by a change in either positive or negative Q4 bias-supply voltages. If the plus and minus bias-supply voltages track, the output changes by the same percent as the bias-supply voltage. Component R3 represents the input resistance of the integrating amplifier and contributes a small error to the output pulse voltage E_o, but its instability makes the unit output unstable.

2.2 Multivibrator Astable State

In the multivibrator astable state, Q4 opens and E_o is determined solely by the negative-bias supply voltage and by the division ratio of R3 and R4. For negative-bias supply-voltage changes, E_o changes by the same percentage as the bias-supply voltage. Changes in tracking-supply voltage (neglecting effect on timing yet to be discussed) introduce the same percentage and direction of change into both positive and negative peaks of E_o. For a completely symmetrical waveform, an increase in peak values would result in no change in the average output. For other than a symmetrical waveform, there is a proportionate change in the average output.

Numerous factors influence time stability of the astable state. The primary timing elements are C1 and R1. Following the positive transition of the multivibrator input (square) waveform, Q1 and Q2 regenerate to the astable state. The junction of R1 and C1 is driven negative by Q1, and the removal of base drive to Q2 results in application of base drive to Q1 via R3. With the great reduction in current through R3 accompanying the change of state, the voltage across R2 drops low enough to cut off Q4. As current through R1 changes, the C1 charge and the voltage at the junction of R1 and C1 reaches zero potential, Q2 finally conducts, and the unit regenerates to the stable state. Termination of the astable state is determined by the resumption of conduction by Q2 when the diode drops of CR1 + $Q2_{be}$ equal the diode drops of CR2 + $Q3_{be}$. These components are chosen to provide the closest possible temperature match. This same match determines the stability of the initial charge on C1 and, hence, the "starting" voltage from which R1 must bring C1 back to zero. This compensation comes as close as possible to the ideal switchover at zero volts, the condition at which the astable period is entirely independent of bias-supply voltage changes (assuming tracking supplies).

3. PACKAGING AND MECHANICAL CONSIDERATIONS

Package size limitations posed a design difficulty. A thin-wall case became necessary despite the use of space-saving welded interconnects in modular construction. The case is thickened at the corners around the mounting holes for adequate rigidity. Two of these corners serve as backing for the compressed gasket which is behind a removable cover plate. This gasket seals the terminal board area against intrusion of moisture. The terminal board utilizes printed wiring to interconnect some of its pins. The printed wiring is double-sided for increased reliability.

With a thin-wall case, it is not practical to use an "O-ring" against humidity. The unit was sealed with a bonding-type silicone rubber coating. This compound is used to form a sealing gasket, which adheres permanently to the bulk case, to the case interfaces at the connector, and to the corners and edges of the package. The encapsulant is Emerson and Cuming ECCO-SIL 4640, a lightweight silicone-rubber material containing glass microballoons.

Although most internal wiring is resistance-welded, some interconnections are made of stranded copper wire. Solid coating of the finished unit protects it from severe environmental conditions. The glass bead and silicone rubber coating is light in weight, moisture resistant, and able to withstand thermal shock conditions.

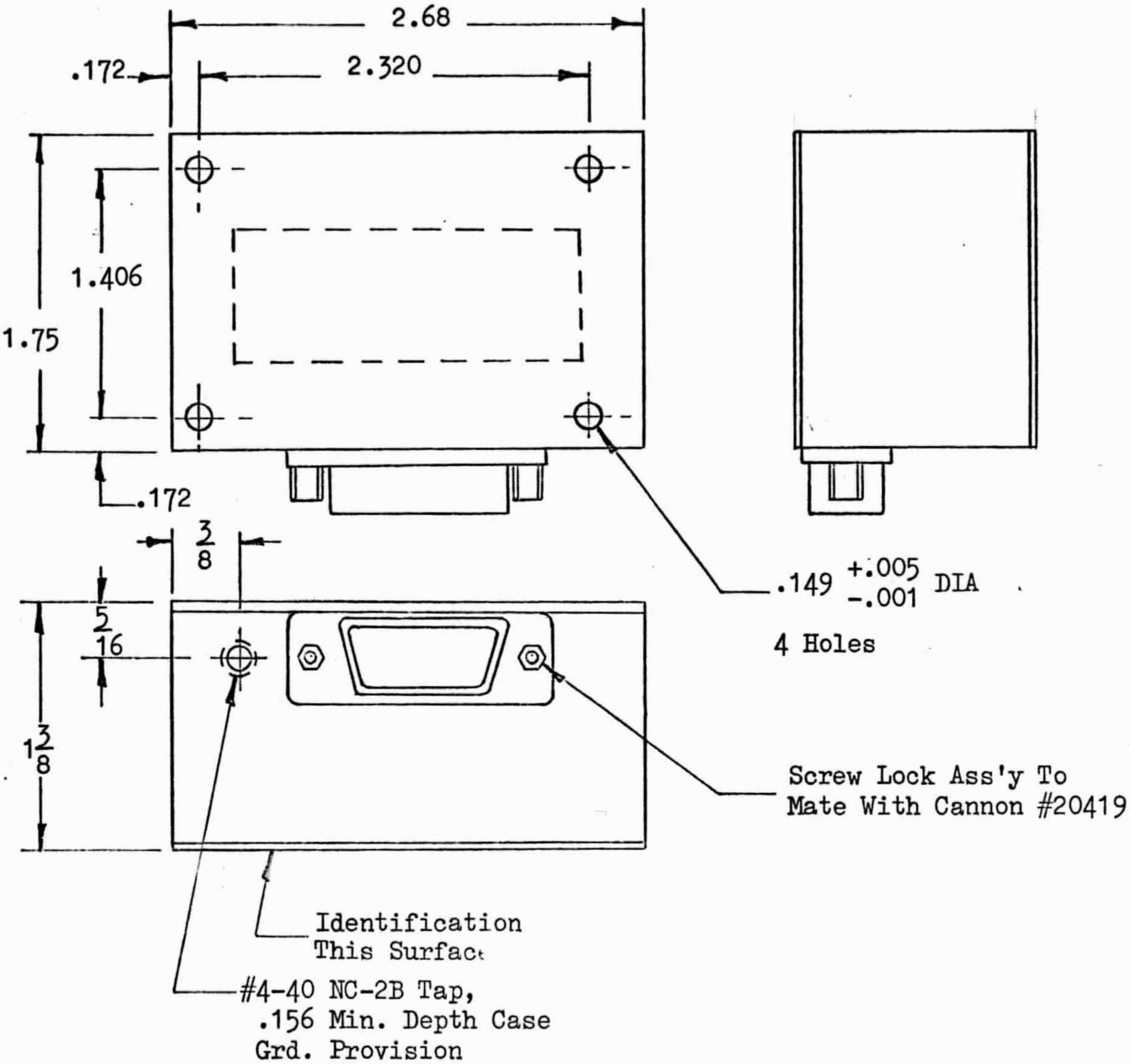
Welded-module construction permits more components to be placed in a small space and is easy to manufacture and test, Figure 4.

4. PRODUCTION PROBLEMS

The most serious production problem encountered was the difficulty involved in determining the proper values of compensation resistors. During early phases of the project, this problem was complicated by an inordinate number of resistor failures resulting from a faulty shipment. All resistors were returned to the manufacturer after determining that there was a 5- to 10-percent failure rate in the stock on hand. Therefore, the production schedule suffered because of the necessity for analyzing and compensating for the resistor failures and for 100-percent testing of resistors before delivery thereafter. The test is a high-power, short-duration resistance check test.

The difficulty in achieving temperature compensation was due to the fact that several of the circuit components have appreciable effect on the temperature stability. Therefore, it was necessary to mate sets of subassemblies with complementary temperature compensations. However, despite these compensations, the original gain stability specification of ±37-1/2 mV (0.75 percent of 5 V) had to be changed to ±125 mV.

During the course of delivery, each preproduction and production unit was returned because of spikes on the input and output ripple. Input spikes were eliminated by the addition of (L1), (C6), (C21), and (R2). Output spikes were eliminated by the addition of (C20) and by the rerouting of wires to shorten leads.



CONNECTOR TYPE: CANNON DAH-15P (MATES WITH DAM-15S)

PIN FUNCTIONS:

1 - (+) Signal Output
2 - Calibrate Energize Input
3 - (+)28V Input
4 - Do Not Use
5 - Calibrate Signal Input
6 - Do Not Use
7 - Case Ground
8 - (+) Signal Input
9 - (-) Signal Output
10 - Do Not Use
11 - 28V Input Return
12 - Spare Wire
13 - Do Not Use
14 - Calibrate Signal Input Return
15 - (-) Signal Input Return

Figure 4. Frequency Standard EMSE-125 Outline

5. ELECTROMAGNETIC INTERFERENCE CONTROL PLAN

The EMSE-125 is designed to minimize effects of electromagnetic interference (EMI). The following design considerations assure compliance with interference requirements.

For minimum conducted and radiated interference:

- Careful component selection and design will reduce transistor and diode switching which causes current spikes.
- Minimize wire length to prevent capacitance coupling caused by fast-switching voltages.
- No shielding is used.
- Utilize L-C networks for suppression of the remaining interference that is not tolerable.

Audio susceptibility is reduced by series L and series regulator at power input.

6. CONCLUDING REMARKS

Electrical tests indicate that the EMSE-125 meets required specifications (Table 1). Figure 5 is a graphic presentation of the average test values obtained from five units. Figure 6 is a group of linearity curves representative of this design.

Test results indicate that this unit is virtually insensitive to the mechanical environment levels (vibration, shock, acceleration) imposed by the specification. The drift characteristics measured during temperature, altitude, oxygen, and humidity environments were within specification requirements. Salt fog environmental tests on early prototype and production units indicated that the unit was not adequately sealed. A small amount of moisture penetrated under the connector and produced

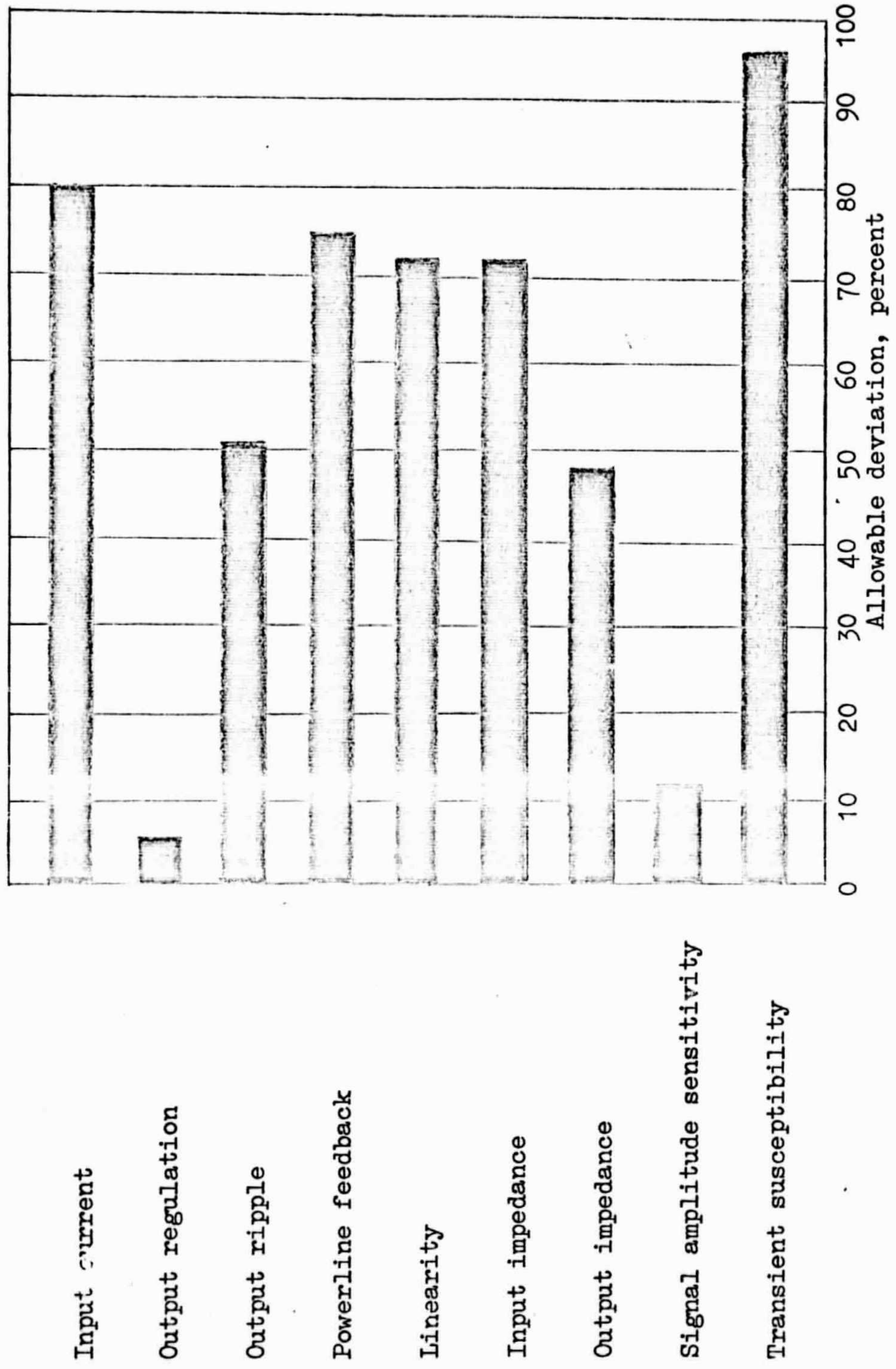


Figure 5. Percent of Allowable Deviation For Model EMSE-125 Frequency Detector

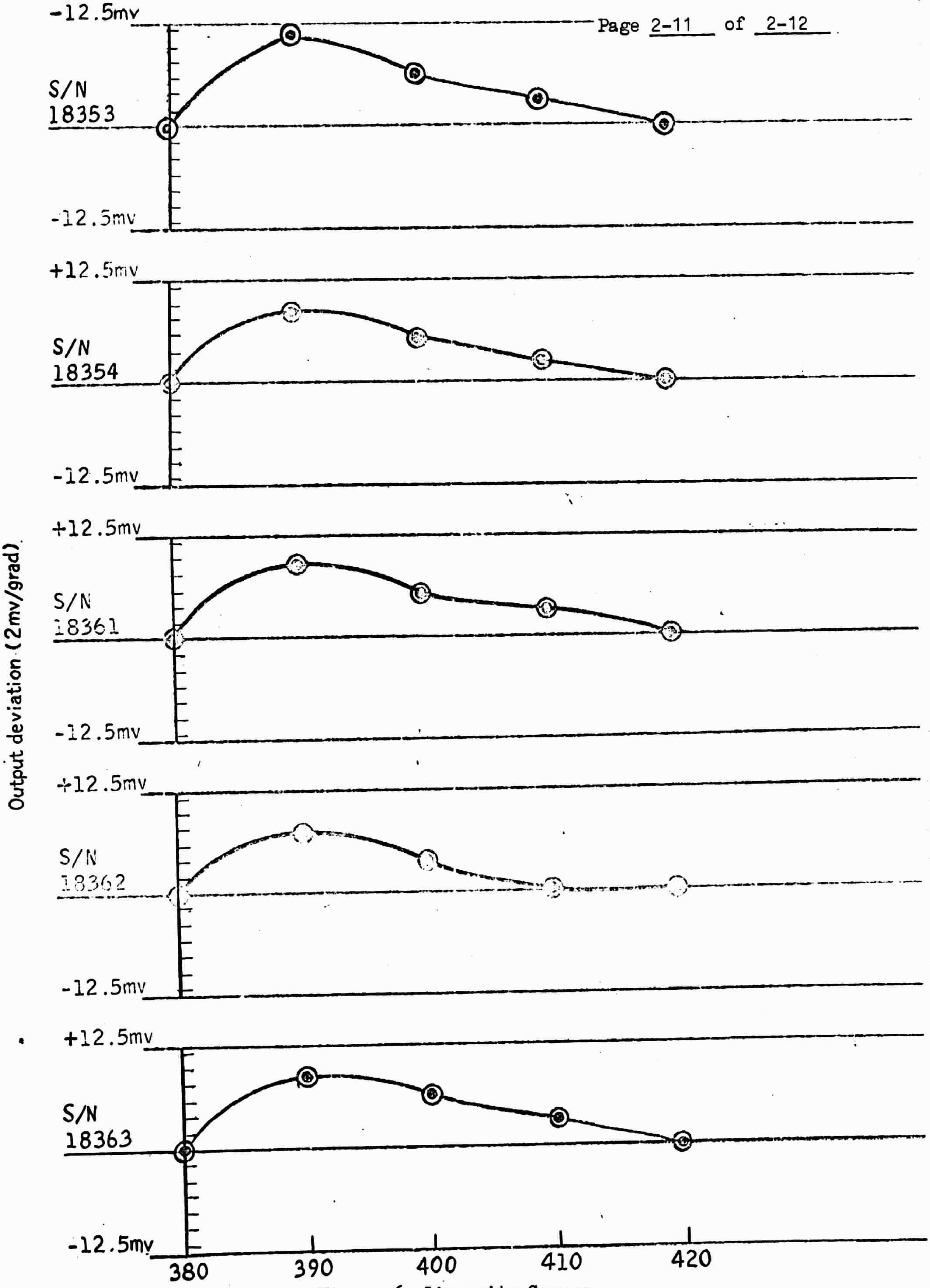


Figure 6. Linearity Curves

partial shorting between pins. Improved potting and sealing techniques have eliminated this problem.

Electromagnetic interference (EMI) tests indicate that the design complies with the requirements of MIL-I-2600, MSC-EMI-10A, and MSC/IESD 19-3. In reducing weight by 70 percent and volume by 75 percent the design of the EMSE-125 represents a significant improvement over previous devices of this type.

APPENDIX A

Environmental Specifications

APPENDIX A - ENVIRONMENTAL SPECIFICATIONS

The information contained in this appendix is based on Environmental Specification MSC/IESD 19-1B (April 1, 1965), developed by MSC.

1. SCOPE

This specification covers:

- Vibration
- Acceleration
- Acoustics
- Temperature
- Humidity
- Vacuum
- Shock
- Salt Fog
- Oxygen
- Sand and Dust
- Fungus
- Hazardous Gases
- Electrical Requirements

Note

Conduct tests in sequence listed if facilities permit.

2. REQUIREMENTS

2.1 Vibration (random and sinusoidal to be used sequentially)

Random and sinusoidal motion shall be applied sequentially along each of three mutually perpendicular axes for 36 minutes. Random spectra are referenced to a log-log plot and held to a ±30 percent power spectral density. The component shall be operative and monitored throughout test.

12.3g root mean square (rms) for 5 minutes

10 cps, 0.01 g^2/cps

10-75 cps, linear increase to 0.14 g^2/cps

75-200 cps, constant 0.14 g^2/cps

200-2000 cps, linear decrease to 0.05 g^2/cps

5g rms for 25 minutes

10 cps, 0.0017 g^2/cps

10-75 cps, linear increase to 0.023 g^2/cps

75-200 cps, constant 0.023 g^2/cps

200-2000 cps, linear decrease 0.0082 g^2/cps

Sinusoidal motion shall be swept logarithmically from 5 cps to 2 kc to 5 cps in 6 minutes in each of the three mutually perpendicular axes. The component shall be operative and monitored thoughout the test.

5-10 cps, constant 0.20 in double amplitude (D.A.)

10-26 cps, constant $\pm$1g

26-56 cps, constant 0.03 in D.A.

56-2000 cps, constant $\pm$5g

2.2 Acceleration

The component shall be subjected to 20g for a time duration of 10 minutes minimum in each direction of three mutually perpendicular axes including whatever time is required to make a functional test. The component is not to be subjected to greater than 20g while increasing or decreasing to test level. The component shall be monitored at all times.

2.3 Acoustic Noise

Components shall be subjected to 165 $\pm$1 dB random noise referenced to 0.0002 dynes/cm^2 for a period of 15 minutes. Octave bands (center frequencies) will be held to $\pm$3 dB. Components shall be monitored at all times.

Octave Band, cps	Sound Pressure Level, dB
22.4 to 45	157
45 to 90	160
90 to 180	159
180 to 355	158
355 to 710	156

Octave Band, cps	Sound Pressure Level, dB
710 to 1400	151
1400 to 2800	145
2800 to 5600	139
5600 to 11200	133
Overall 165 dB	

2.4 Temperature (at atmospheric pressure, -65° to +160°F)

The following steps shall be followed during the 5-day temperature cycle. The component shall be mounted in the chamber in a manner which ensures adequate circulation around all surfaces.

a. Reduce temperature to -65°F and soak for 4 hours ±15 minutes. The component shall be in a deenergized condition. No operational check is required.

b. Increase temperature to 100 ±5°F in 30 ±10 minutes. Energize and soak for 4 hours Conduct an operational test. Record time, temperature, and data; deenergize equipment.

c. Increase temperature to 160 ±5°F in 15 ±5 minutes and soak for 24 ±1 hours. Energize components during the last 30 minutes; conduct an operational test. Record time, temperature, and data; deenergize component.

d. Decrease temperature to 0 ±5°F in 15 ±5 minutes and soak for 24 ±1 hours. Energize component during the last 30 minutes; conduct an operational test. Record time, temperature, and data; deenergize equipment.

e. Continue cycling as in steps c and d except with component energized during the last 36 hours. Conduct an operational check at room ambient temperature at conclusion. Record temperature, time, and data. The Time-Temperature table for energizing is as follows:

Hours	4	4	24	24	24	24	24
Temp, °F	-65	+100	+160	0	+160	0	+160
Energized	no	yes	30 min	30 min	30 min	12 hr	yes

2.5 Humidity

One hundred percent humidity including condensation for 5 days in a temperature range of 80 to 160°F. Temperature cycling shall be maintained as in MIL-STD-810 (USAF) Method 507. The component shall be operative during last 30 minutes.

2.6 Altitude

a. Stratosphere-ionosphere environments

Ambient pressure to 100,000 + 10,000 feet or -0 feet, equivalent pressure in 2.5 + 0 minutes or -0.5 minute; continue to 200,000 + 50,000 feet or -0 feet, and hold for 30 minutes. The component shall be operative.

b. Deep space environment

Nominal 5 days at 1×10^{-6} mm Hg pressure or less for 5 days. The components shall be operative 2 hours each 24-hour period.

2.7 Shock

Shock impulses at 30g for 11 $\pm$1 msec. There shall be 3 shocks in each direction of three mutually perpendicular axes for a total of 18 shock impulses. Shock input will be a saw-toothed waveform with 10 $\pm$1-msec rise and 1 $\pm$1-msec decay time. The component shall be operating during test.

2.8 Salt Fog

As in MIL-STD-810 (USAF) Method 509 (equivalent to spray or 5-percent salt solution in water for 50 hours).

2.9 Oxygen Atmosphere

One hundred percent atmosphere at 5 PSIA for not less than 5 days. The component shall be operative 10 minutes each 24-hour period.

2.10 Sand and Dust

Sand and dust are such as encountered in desert and ocean beach areas (equivalent to 140-mesh silica flour with a particle velocity up to 500 feet per minute) and as described in MIL-STD-810 (USAF) Method 510.

2.11 Fungus

The fungus test will be conducted as specified in MIL-STD-810 (USAF) Method 508 on components containing nutrient materials. Whenever possible, fungus resistant materials as defined in MIL-E-5400 should be used.

2.12 Hazardous Gases

In the event of a short circuit, the nonmetallic materials shall not give off products that are deleterious to the astronaut at the temperature at which the material fuses.

At low pressure and/or high temperatures, there shall be no outgassing containing nauseous, toxic, or harmful components such as carbon dioxide, carbon monoxide, hydrogen sulfide, sulfur dioxide, methane, indole, skatole, mercaptans, ozone, and similar compounds which shall result in decreased performance capabilities of the astronaut.

2.13 Electrical Requirements

Operating voltage shall be 28 ±4 VDC. No damage will occur to the component with a constant input voltage of 37 VDC for 10 minutes. The component output data shall not vary over ±1 percent during application of four-volt peak-to-peak ripple (DC to 2 KC square wave), imposed on the 28-V bus. The component shall operate with less than 10-percent performance degradation with the input voltage between 22 and 24 VDC.

The transient susceptibility test shall be performed as described in this paragraph. The components shall survive a minimum of 10 negative 28-V pulses and 10 positive 15-V pulses with a rise time of

8 msec or less, a time base of 20 msec, and at a random pulse repetition frequency. This pulse will be applied to the input bus with the component operating at 28 VDC.

Feedback ripple shall be measured across a 1-ohm resistance inserted in series with the power source and will be less than the following values:

a. 30 mV peak-to-peak for any component drawing less than 1 ampere of current at 28 V

b. 100 mV peak-to-peak for a component drawing between 1 to 3.5 ampere of current at 28 V

c. 150 mV peak-to-peak for a component drawing between 3.5 to 8 ampere of current at 28 V

Reverse polarity of input power for 10 minutes shall not damage component. Isolation resistance between primary power input and signal output shall exceed 20 M-ohm at 100 VDC.

2.14 Design and Testing

Components shall be designed and tested in accordance with MIL-I-26600/MSC-EMI-10A.