where

$$y^{(i)} = \frac{1-\gamma^{(i)}}{1+\gamma^{(i)}}. \quad (21)$$

$y^{(i)}$ is the normalized admittance at the plane $Z = 0$.

From (20), we have the following variational expression [3] for $y^{(i)}$:

$$y^{(i)} = \frac{\int_0^{a/2}\int_0^{a/2} G^{(i)}(x/x')\epsilon^{(i)}(x)\epsilon^{(i)}(x')\,dx\,dx'}{Y_{01}\left[\int_0^{a/2}\epsilon^{(i)}(x)\phi_1\,dx\right]^2} \quad (22)$$

where

$$G^{(i)} = \sum_{n=3} Y_{on}\phi_n(x)\phi_n(x') + \sum_m Y_m Q_m^{(i)}\Psi_m(x)\Psi_m(x')$$

$$Q_m^{(1)} = \coth\frac{T_m W}{2}$$

$$Q_m^{(2)} = \tanh\frac{T_m W}{2}.$$

The trial function ϵ is given by

$$\epsilon = \sum_\nu m_\nu \sin\frac{2\nu\pi x}{a-t}, \qquad \nu = 1,2,3,\cdots N. \quad (23)$$

Substituting (23) into (22), we get

$$y^{(i)} = \frac{\sum_{n=3} Y_{on}(\sum_{\nu=1}^{N} A_{\nu n}m_\nu)^2 + a\sum_{\nu=1}^{N} m^2_\nu Y_\nu Q_\nu^{(i)}}{Y_{01}(\sum_{\nu=1}^{N} m_\nu A_{\nu 1})^2} \quad (24)$$

where

$$A_{\nu n} = (-1)^\nu \frac{8_\nu a^{1/2}}{\pi(n^2-4\nu^2)}.$$

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A Computerized Klinger Cavity Mode Conversion Test Set

BARRY S. SEIP AND LARRY W. HINDERKS

***Abstract*—A mode conversion test set utilizing the Klinger cavity technique has been developed for characterizing circular waveguide components in the millimeter waveguide region. The test set incorporates a precision linear displacement optical encoder and a specially designed controller which interfaces the test set to a Hewlett-Packard 2100 series computer. Control commands of a stored computer program are used by the operator for data acquisition and analysis. Experimental results show this system has high measurement accuracy and sensitivity while maintaining an uncomplicated measurement process.**

INTRODUCTION

TO MEET increasing communication needs, Bell Laboratories is engaged in developing a millimeter waveguide transmission system. This circular 60-mm-diam waveguide uses the TE_{01}° mode and operates from 40 to 110 GHz. It will have a capacity of approximately $\frac{1}{4}$ million voice circuits.

In developing the waveguide system, measurement components are needed to transform the $TE_{10}^{\square}$ mode into the TE_{01}° mode in the 60-mm-diam waveguide. A combination of a transducer, mode filter, and helix taper is used to make the necessary transition from the millimeter wave source to the waveguide module being characterized. The TE_{01}° mode launching components are used in determining the TE_{01}° mode transmission characteristics of the waveguide modules. TE_{11}° and TE_{12}° mode launchers have been designed for determining the unwanted mode attenuation of waveguide modules. The modal purity of all transducers and tapers must be known before they can be reliably used in test sets. The Klinger cavity method [1] is a powerful method for determining modal purity.

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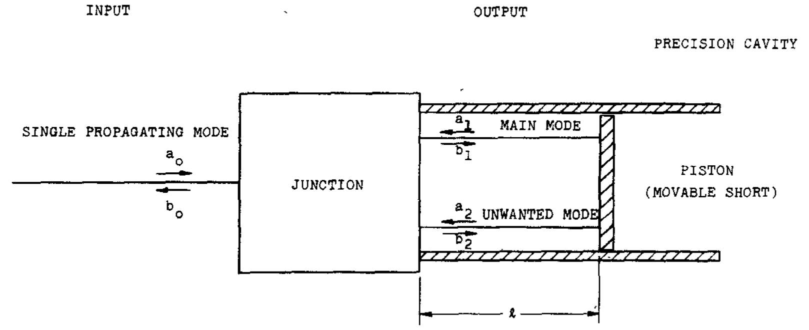


$$\begin{bmatrix} b_0 \\ b_1 \\ b_2 \end{bmatrix} = [s] \begin{bmatrix} a_0 \\ a_1 \\ a_2 \end{bmatrix} \qquad s = \begin{bmatrix} \Gamma_{00} & \Gamma_{01} & \Gamma_{02} \\ \Gamma_{01} & \Gamma_{11} & \Gamma_{12} \\ \Gamma_{02} & \Gamma_{12} & \Gamma_{22} \end{bmatrix}$$

$\Gamma_{02} = \frac{b_2}{a_0}$ when $a_1 = 0 = a_2$ is the required coupling coefficient.

$\Gamma_{11} = \frac{b_1}{a_1}$

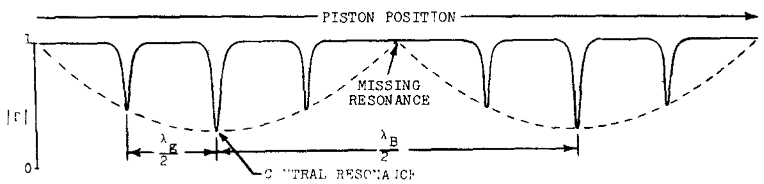
if: 1) The input is matched when the two lines are separately matched. This implies $\Gamma_{00} = 0$

2) Most of the energy is in the main mode $|\Gamma_{01}| >> |\Gamma_{02}|$

3) The loss of the transducer can be neglected.

4) The loss of the main mode line may be neglected. $|\Gamma_{11}'| = 1$

Fig. 1. Three-port representation of a mode converting junction.



$\frac{c}{f} = \lambda_0$ = free space wavelength

$\frac{1}{\lambda_g^2} = \frac{1}{\lambda_0^2} - \frac{1}{\lambda_c^2}$ λ_g = unwanted mode guide wavelength

$\frac{\Pi D}{X_1} = \lambda_c$ = unwanted mode cutoff wavelength

$\lambda_B = \left|\frac{\lambda_m \lambda_g}{\lambda_m - \lambda_g}\right|$ λ_m = main mode guide wavelength

λ_g = unwanted mode guide wavelength

$\Gamma = \frac{b_o}{a_o}$ a_o = incident main mode amplitude

b_o = reflected main mode amplitude

c = speed of light

f = frequency of measurement

D = Diameter of cavity

X_1 = Eigenvalue of mode

Fig. 2. Ideal Klinger data.

THE KLINGER METHOD [1]

A simplified diagram which illustrates the Klinger method of measuring mode conversion is shown in Fig.1. The letters a and b refer to the incident and reflected modal amplitudes, respectively. The subscripts 0, 1, and 2 refer, respectively, to the input mode, the output main mode, and the unwanted mode. Certain assumptions about the theory must be understood before the Klinger technique can be accurately used. It is assumed that one pure mode (a_0) is incident on the junction from a nonreflecting source. The incident mode is not reflected at the junction and is coupled strongly to the output main mode in the forward direction. If the transducer is imperfect, unwanted modes are generated at the junction which are small in comparison to the level of the main mode. All interaction between the incident, main, and unwanted modes takes place within the junction. The unwanted mode (a_2) is highly reflected at the junction and the energy coupled to this mode is trapped in the cavity. The reflected main mode a_1 is not reflected strongly at the junction and coupled to b_0. From these assumptions, Klinger analyzed such a system using a 3-port representation as shown in Fig. 1. Each unwanted mode is analyzed individually with respect to the main mode.

As the piston, which serves as a short circuit, is moved in the cavity, there are certain positions such that the length (l) of the cavity is an integral multiple of half-guide wavelengths for an unwanted mode. The half-guide wavelength is determined by the cavity diameter, the measurement frequency, and the unwanted mode (Fig. 2). At these positions the unwanted mode is resonant causing its field magnitude to increase. The energy driving the unwanted mode is coupled from the incident mode at the junction. Therefore, the returning mode amplitude (b_0) must dip as the piston passes through the resonating position (Fig. 2). The amount of coupling into the unwanted mode can be determined from the magnitude of the standing wave of the incident mode at a central resonance. The unwanted mode is identified by the spacing between its resonances which is one-half its guide wavelength.

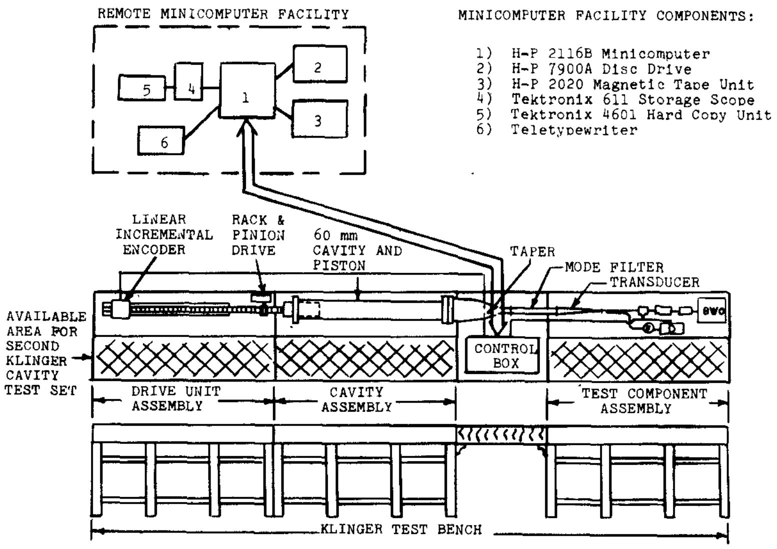


Fig. 3. The new Klinger cavity test set.

A computer-controlled technique for making Klinger resonance cavity measurements is described in this paper, including the mechanical and electrical design and the interactive computer program. Finally, some initial measurement results are given. This test set is more accurate, has greater sensitivity, and has greatly reduced measurement time as compared to manual methods using an $X-Y$ recorder and oscilloscope.

THE COMPUTERIZED KLINGER CAVITY TEST SET

The Klinger cavity test set (Fig. 3) incorporates many devices and design improvements which overcome many of the basic limitations of previous methods. The test set operates under the control of an interactive computer program. The system features automated data acquisition and operator–computer interaction for data analysis. Sequential data pairs representing relative reflected power versus piston displacement are collected at increments of 1.27 or 2.54 μm (Fig. 4) and stored on the computer's mass storage peripheral. A linear incremental encoder, connected to the piston drive, provides the spacing information. After the data are stored in the computer, they are analyzed using the Klinger analysis language (KAL). KAL is an interactive computer program used for data acquisition and data analysis. Through the use of the stored computer program, the operator manipulates the data by using the teletypewriter. The program displays the requested data on the display peripheral (storage scope). The operator can then selectively measure the unwanted mode levels in a manner conceptually similar to the manual method.

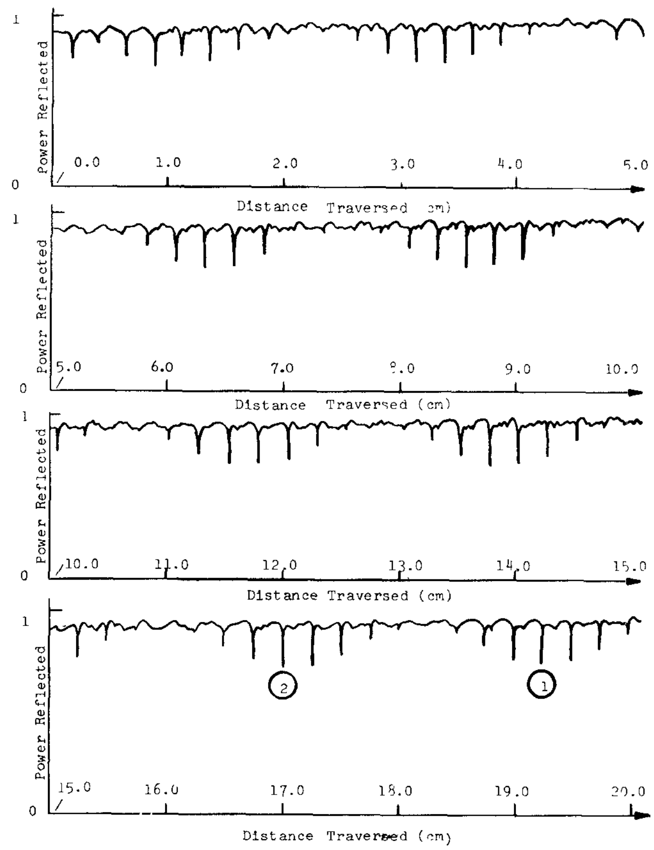


Fig. 4. Klinger data for transducer 3 at 75.0 GHz.

The operating sequence of the new test set is as follows. The backward-wave oscillator is operated at a single frequency. The piston is driven by the drive unit and pulses are obtained from the linear incremental encoder (1.27 or 2.54 μm). These pulses and the analog voltage representation of RF power reflected are the inputs to the control box, which is the interface between the Klinger test set and the computer. With each pulse from the encoder, the analog voltage is digitized in the control box by a 12-bit analog-to-digital (A–D) converter. This digital information is passed to the computer where it is stored on the magnetic tape unit. A magnetic tape is used because of its fast sequential writing speed as compared to the relatively long latency time of a disk storage peripheral. At the conclusion of the data run, the information is transferred from the magnetic tape to the disk where it is manipulated and analyzed by the use of KAL. Each word of data contains both distance and relative reflected power information. Errors due to frequency and amplitude drift are minimized since the data are acquired and stored in about 5 min.

Using KAL, mode identification is accomplished by absolute measurements of unwanted mode half-guide wavelengths (Fig. 5). In a 60-mm waveguide, guide wavelengths are 2 – 5 mm from 40 to 110 GHz but wavelength differences between modes of only a few micrometers are not uncommon. For example, at 110 GHz in a 60-mm waveguide, the wavelengths for the TE_{01}° mode and the TE_{11}° mode are 2920 and 2916 μm, respectively. Since mode identification is accomplished by measuring the half-guide wavelengths, the high resolution linear incremental encoder provides the needed precise distance information.

Using this test set, enough data are collected to cover at least one half-beat wavelength for the modes of interest. For the previous example the half-beat wavelength for $TE_{01}^{\circ} - TE_{11}^{\circ}$ is 0.75 m. The test set acquires data for up to 1.25 m of piston travel which is equivalent to about one million data points.

With this test set, KAL is used to measure, absolutely, the central resonance reflection coefficient (Γ_0) and the central resonance full width at half power (L) (Fig. 5). The width is easily determined, when the data are collected by a linear incremental encoder, by counting

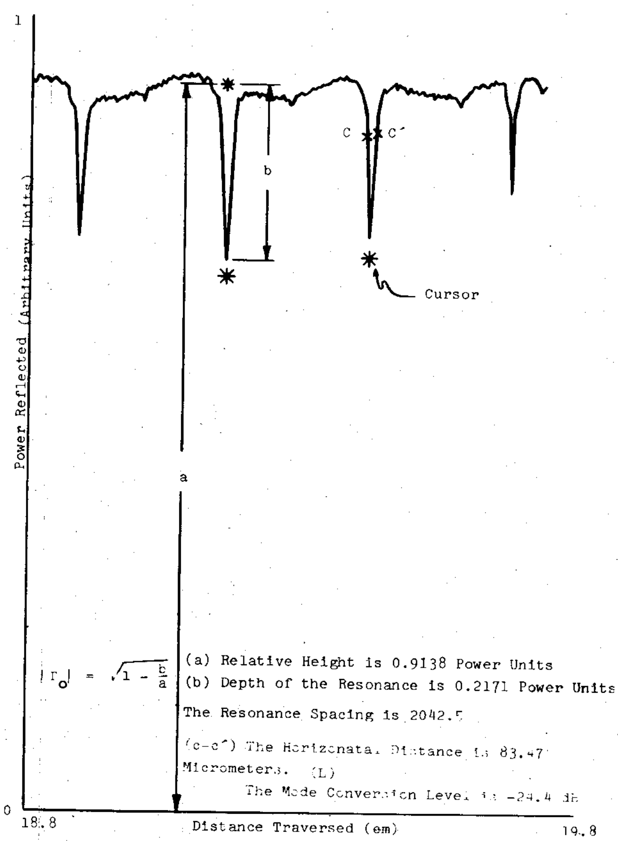


Fig. 5. Expanded view around resonance 1 (Fig. 4).

the distance between the half power points. After these measurements are completed, KAL calculates the unwanted mode level (λ_{02}) from the following equation [1]:

$$|\lambda_{02}\,(\text{dB})| = 10 \log_{10} \frac{\beta L}{4} (1 - \Gamma_0) \tag{1}$$

where β is the waveguide propagation constant of the unwanted mode in the circular cavity.

MECHANICAL DESIGN

To achieve the most accurate experimental results, the Klinger cavity test set was built on a specially constructed level surface. Steel base plates are chosen on which subplates of component assemblies are placed (Fig. 6). The individual base plates are leveled to within 50 μm (2 mil). The cumulative error of the test set alignment is less than 380 μm (15 mil). Thus little mode conversion is caused by curvature or misalignment. The waveguide bands of test components are preassembled and can be interchanged in the test set with minimal effort. To make the test set versatile, an arrangement is chosen so two large diameter cavity (60-mm) Klinger test sets or one large and one small diameter cavity (4.5–13-mm) test set are placed on the available area (Fig. 7). The large Klinger cavity test set is used to test tapers and other 60-mm waveguide components. The small Klinger is used to test transducers and mode filters. The drive unit assembly consists of a rack and pinion drive and the linear incremental encoder. The encoder consists of an optical head and a graduated scale. The scale is mounted in a precision holder and the optical head is supported by ball bearings which ride on the holder. The head is connected directly to one end of the rack holder. The other end of the rack holder connects to the piston through a special universal joint. The joint is constructed, using spherical bearings, to have little axial movement. Using this design, the encoder tracks the movement of the piston exactly. All gear backlash is external to the piston to encoder connection. Cavity mounts are designed using magnetic V blocks to prevent deformation of the precision cavity. The waveguide component subassemblies are set in guide rails on the

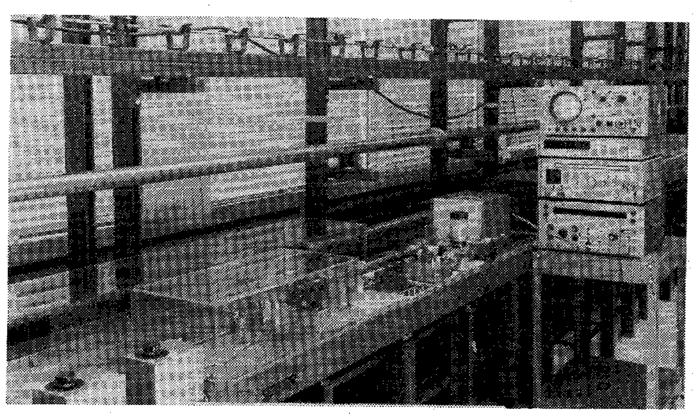


Fig. 6. Klinger cavity test assembly.

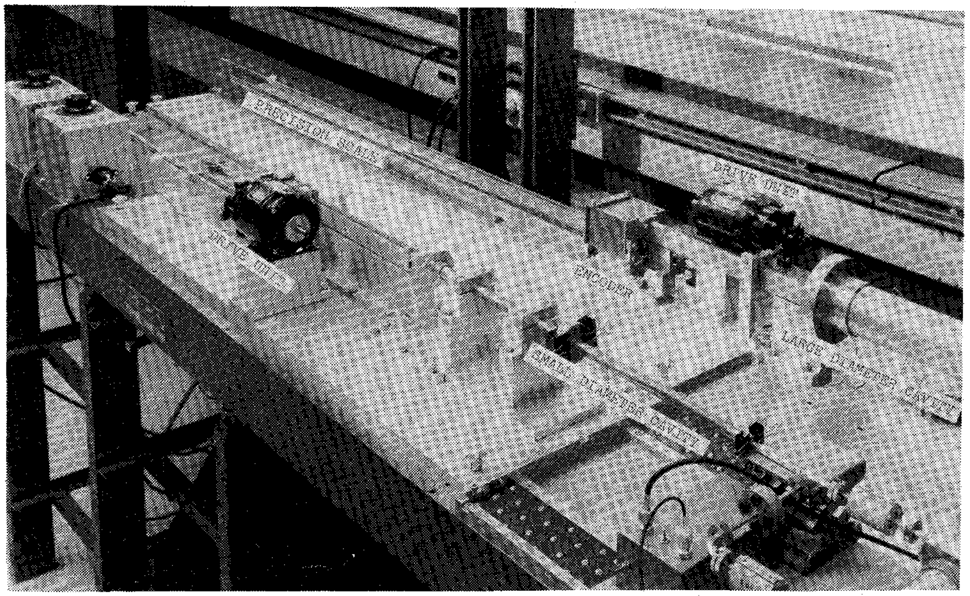


Fig. 7. Large and small diameter Klinger cavities, drive units, and precision scales and encoders.

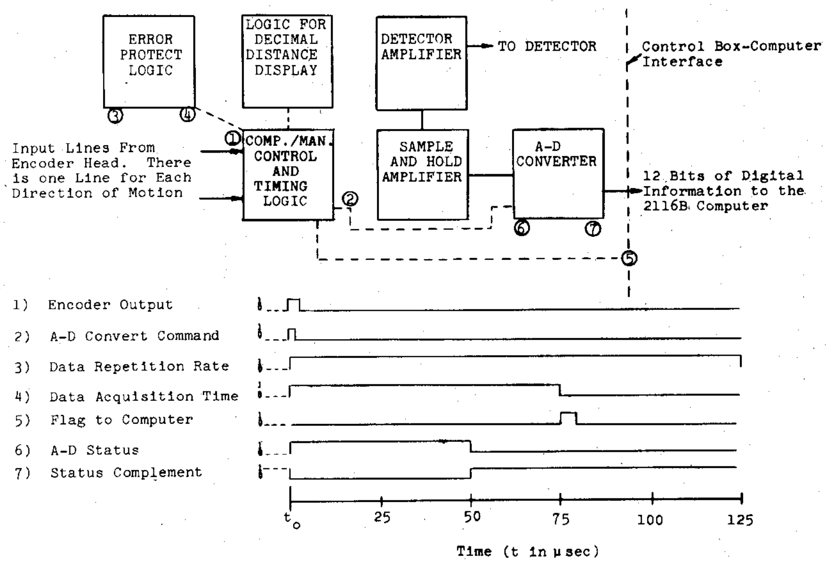


Fig. 8. Block diagram and timing sequence of the control box.

base plate. Under the component subassembly are ball bearing parallels which allow free axial movement of the waveguide test components (Fig. 7). Axial movement is needed to allow for the variety of lengths of the test components.

ELECTRICAL DESIGN

The Klinger cavity test set is designed to interface with Hewlett-Packard 2100 series computers (Fig. 3). The computer facilitates the measurements because of its speed and accuracy in performing arithmetic operations and its ability to hold large volumes of data. A control box (Fig. 8) is the electrical interface between the computer and the Klinger test set (Fig. 3). A major function of the control box is to digitize the analog voltage from the detector. The control box also includes logic circuits for computer or manual control of the piston drive unit and a digital readout of the distance traversed by the piston. It is extremely important in the data analysis to have accurate data transfer to the computer. Therefore, a special logic circuit is included in the control box to protect against erroneous data caused by the piston momentarily reversing direction or being driven too fast for data acquisition. The timing sequence for one data transfer is shown in Fig. 8.

A movable cursor ("joystick") (Fig. 9) is used in conjunction with the data analysis computer program. The "joystick" is an electronic pair of dividers used for measuring half-guide wavelengths and resonance half power widths. A subroutine, servicing the joystick, uses the position information of the joystick to generate a cursor on the storage scope (Fig. 5). The cursor position can be recorded in the computer by depressing the storing button on the joystick. The position of the cursor is also

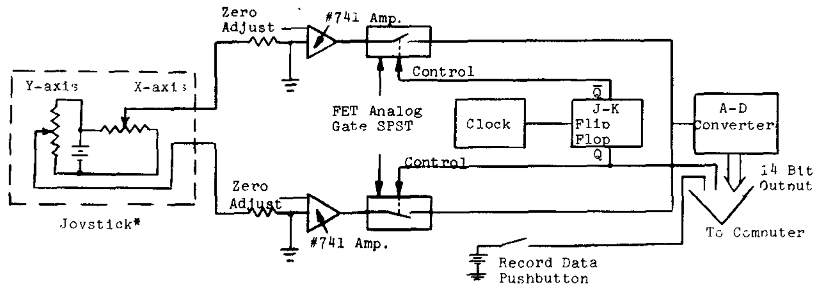


Fig. 9. Block diagram for the joystick. *: measurement systems model 525 X–Y positioner.

stored on the screen of the display unit. The computer program can then resolve horizontal or vertical distance between any two cursor marks.

COMPUTER SOFTWARE

A special computer program—KAL—is used in the operation of the Klinger test set (Fig. 3). KAL consists of 15 commands which are used to acquire and analyze the measurement data. The basic structure of the program is to have commands for data acquistion, data manipulation, and data reduction. In the data acquisition phase one command initiates the acquisition of sequential data pairs which are automatically stored on the magnetic tape unit. After a data run is complete another command is used to dump the data to the disk. From the disk, data can be manipulated and displayed on the storage scope by other commands of KAL. When data are displayed that resemble the beating pattern (Fig. 2) for a mode, the data reduction commands are used. These commands are used to measure the resonance spacing (Fig. 5), the resonance depth, and the resonance half power width (Fig. 5). The measurements are accomplished using the joystick to manipulate a cursor on the storage scope. When these measurements are complete the mode conversion level for the unwanted mode is calculated using (1).

MEASUREMENT RESULTS

As a verification that the computerized Klinger test set and KAL were working properly, test measurements were made on a WR-15 TE_{10}□-TE_{01}○ transducer. The output diameter is 9.52 mm. Therefore, a 9.52-mm-diam cavity and piston were connected to the transducer output utilizing the area for another test setup as shown in Fig. 3. This particular transducer was previously characterized using the manual method. The results from the two measurements are shown in Fig. 10.

The data show that the computerized test is more sensitive than the conventional method. For example, the TE_{31}○ level at 62.0 GHz was too low to measure using the conventional method but a level of -35.9 dB was measured using the computerized test set at the same frequency. The additional sensitivity estimated at approximately -40 dB for the small diameter mode conversion measurements is due to careful shielding to reduce

	X-Y RECORDER TEST SET RESULTS		COMPUTERIZED KLINGER TEST SET RESULTS	
Frequency (GHz)	TE°_{11}(dB)	TE°_{31}(dB)	TE°_{11}(dB)	TE°_{31}(dB)
60.0	-22.5	-32.2	-22.7	-30.2
62.0	-23.7	*	-21.9	-35.9
64.0	-23.1	*	-21.5	-
66.0	-21.9	*	-20.3	-
68.0	-22.5	-33.0	-21.0	-30.7
75.0	-23.9	*	-24.4	-36.0

Fig. 10. Mode conversion results for WR-15 TE_{10}□ − TE_{01}○ transducer. *: detected (too low to measure; -: detected (not measured).

crosstalk noise, an improved calibration technique for the diode detector, and the ability of the KAL program to increase the horizontal and vertical scale sensitivities, thus allowing more accurate measurements of small resonances.

At higher mode conversion levels, where one would expect noise not to interfere, the results differ by about 2 dB. At first this seems to be a large variation but an investigation using the computerized test set resolved the discrepancy. The approximations made in arriving at (1) assume the data are an ideal symmetrical beat pattern (Fig. 2). Therefore, to assure minimum error one must measure the central resonance in the beat pattern that best approximates the ideal type. The data using the computerized set extended over many beat wavelengths (Fig. 4). This allows the experimenter to make the mode conversion measurements on resonances which closely approximate the ideal pattern. Since all measurements using the computerized test set were made on resonances with beat patterns closely resembling the ideal pattern, the resulting unwanted mode levels are more accurate.

CONCLUSION

An automated test set to accurately determine mode conversion levels of various circular waveguide millimeter wavelength components has been designed and constructed. This test set allows a greater dynamic range of mode conversion amplitudes to be measured and makes it possible for accurate measurements to be performed in a minimal amount of time.

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