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Final Technical Report

March 1988

AN INVESTIGATION OF THE USES OF TIME DOMAIN CAPABLE VECTOR NETWORK ANALYZERS AS A DIAGNOSTIC FOR HELIX TRAVELING-WAVE CIRCUITS

University of Utah

James V. Davis, II

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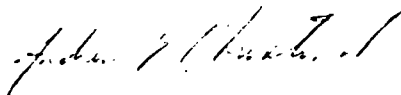
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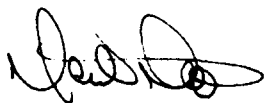
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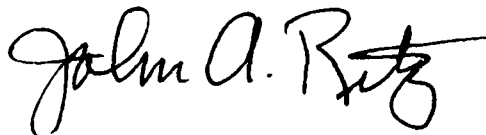
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The purpose of this project is to investigate the uses of time domain capable vector network analyzers as diagnostics for the design and test of helix traveling-wave tubes (TWT's). The uses of the time domain (TD) investigated included tracking the location of a bead in the circuit, determining the phase velocity versus frequency using the gating methods available in the time domain, and locating faults and discontinuities along the helix circuit. Good agreement with expected results were obtained for the phase velocity versus frequency in a 2-8 GHz circuit, except at the band edges, and uses for fault location were demonstrated. Another method was devised using the complex nature of the data without going into the time domain to measure phase velocity versus frequency data. This method proved to be more accurate overall than the time domain method.					
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TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	iii
LIST OF ILLUSTRATIONS AND TABLES	v
I. INTRODUCTION	1
II. EXPERIMENTAL SET-UP	2
III. TIME DOMAIN MEASUREMENTS	4
A. General Theory and Capabilities	4
B. Preliminary Investigation	7
1. Response of Helix Circuits	7
2. Bead Tracking	8
C. Determination of v_p Versus f Using Gating	12
1. Verification of Method	13
2. Testing of Actual Circuits	19
D. Fault Location	22
IV. FREQUENCY DOMAIN MEASUREMENTS	26
A. General Theory	26
B. Automation of Measurements and Calculations	26
C. Comparison of Results with Known Phase Data	27
V. CONCLUSION	36
APPENDIX A. DERIVATION OF PHASE VELOCITY MODEL FOR FREQUENCY DOMAIN	39
APPENDIX B. COMPUTER PROGRAMS	42
APPENDIX C. DESCRIPTION OF METHODS USED TO GET COMPARISON DATA .	51
REFERENCES	53

LIST OF ILLUSTRATIONS AND TABLES

<u>Figure</u>		<u>Page</u>
1	A typical response of a helix cold test circuit. The first response is due to the input discontinuity, and the second to the output discontinuity	9
2	The response of a helix cold test fixture with no bead, and with the bead at two different positions	10
3a	The ideal response of the circuit shown in Fig. 3b. This response is intended to model the type of response seen in helix circuits. The first response is a composite response due to the input window/helix-to-pin connection, and the last response is due to the bead	16
3b	An equivalent circuit used to model the response of a helix circuit and bead	17
4	An equivalent circuit used to model the helix circuit response. This circuit is used to examine the effect of varying the phase velocity at different points in the circuit	17
5	Comparison of results obtained from the gating method to those obtained by the resonance method for a 2-8 GHz helix circuit. Mean diameter and pitch are 0.151" and 0.088", respectively	20
6	The response of a circuit with an opened helix-to-pin connection, as well as the response before the open occurred	23
7	A melted (opened) helix approximately one inch past the input connection in the time domain	24
8	An example of the output from the REFEQ program at one frequency	28
9	Comparison of results obtained using the REFEQ program with those obtained by the bead pull method. Circuit mean diameter is 0.1174" and pitch is 0.028"	31
10	Comparison of results obtained for a second circuit tested using the program REFEQ with those obtained using the resonance method. Circuit diameter and pitch are 0.151" and 0.088", respectively	33

<u>Figure</u>		<u>Page</u>
11	Comparison of results for the IJ band circuit obtained using the REFEQ program with those obtained using the bead pull method. Circuit mean diameter and pitch are 0.0723" and 0.045", respectively	35
B.1	Example of input data file for REFEQ program	44

Table

1	Comparison of the physical distance moved by the bead (z column) with the value calculated from the peak of the bead's response in the time domain (delta z column). v/c was assumed to be 0.205 to make the calculations . . .	11
2	Comparison of the actual bead location to peak-of-bead response in the time domain	12
3	The angle of the reflection coefficient for the total circuit, the first mismatch alone, and the second mismatch alone for an ideal circuit consisting of a 50 to 75 to 50 ohm transmission line	14
4a	The phase shift resulting from several consecutive 0.5 cm shifts in the bead position at 10 GHz. The expected shift is 120 degrees	18
4b	The phase shift resulting from two consecutive 0.5 cm shifts in the bead location at 12 GHz. The expected shift is 144 degrees	18
5	Comparison of the normalized phase velocity found using the gating method on the ANA with that found using the resonance method on a 2-8 GHz circuit	21
6	The results of running the program REFEQ for the first circuit tested. The average phase constant, normalized phase velocity, and variation in the results are shown . .	29
7	Comparison of the results obtained using the ANA to calculate normalized phase velocity with that obtained using the beam pull method	30
8	The results of running the program REFEQ for the second circuit tested. The average phase constant, normalized phase velocity, and variation in the results are shown . .	32

9	Comparison of the results obtained using the ANA to calculate normalized phase velocity with that obtained using the resonance method for the second 2-8 GHz circuit tested	34
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I. INTRODUCTION

This project explores the uses of time domain capable vector network analyzers as a diagnostic in helix traveling-wave tubes. The automatic network analyzer (ANA) used throughout the experiments was the Hewlett Packard 8510 ANA with the time domain option.

In Section II of this paper, the experimental set-up used for these experiments is discussed.

In Section III of the paper, the uses of the time domain are investigated. The first section gives some general theory of time domain analysis and some of the items of concern when using a network analyzer with time domain capability. The preliminary investigations involved looking at the typical response of helix circuits, both for special cold test circuits and actual helix circuits. Also investigated was the ability of the ANA to resolve a bead perturber as it moved along the circuit. Next, a method of determining the phase velocity versus frequency was devised and tested on ideal circuits, an airline circuit, and finally on actual tube circuits. The final use of the time domain that was investigated was the more traditional use of locating faults or discontinuities as a function of distance in the circuits.

In Section IV of the paper, the complex vector nature of the data obtained from the ANA is exploited to enable one to obtain phase velocity as a function of frequency without going into the time domain. The general theory behind the method is discussed, along with the model used to calculate the phase velocity and the method of taking data. The results are then compared with previously obtained data to illustrate the accuracy of the method.

II. EXPERIMENTAL SET-UP

The measurements in this paper were all made using a metallic bead as a perturbing object, as has been suggested in the literature dealing with perturbation techniques.¹ The bead was suspended on a thin nylon line and drawn down the axis of the circuit. In these types of measurements, it is imperative to insure that the perturbing object is centered in the circuit being measured in order to get accurate results.

In order to get some control over the position of the bead in the circuits, a fixture was made to hold the circuits while measurements were being made. To facilitate centering of the bead, the circuit was placed in a cradle and secured in place with tie downs. This cradle was designed to have some movement in the horizontal direction so as to be able to get the string straight down the circuit. Vertical adjustability was incorporated into the connection to the slotted line carriage and also to the pulley at the other end. The line is attached to the carriage, threaded through the circuit, and then hung over the pulley with a weight to provide tension in the line. With adjustability in both directions, it is then easy to get the bead to travel along the axis. The slotted line carriage has a scale on it that is accurate down to one hundred micrometers. For increased accuracy in positioning, a high resolution stepper motor would be the best solution, and should result in much better repeatability than moving the carriage by hand. A stepper motor could also be programmed to make the movement of the bead automatic.

The ANA was used both manually and controlled by an HP series 200 computer. The computer could be used to control a stepper motor to make the measurements semiautomatic, although some user input would still be needed for the time domain methods.

III. TIME DOMAIN MEASUREMENTS

A. General Theory and Capabilities

Before going into the results of the investigation of the uses of the TD capabilities for TWT's, an overview of the general theory and the specific abilities of the HP8510 vector network analyzer will be presented. For a more in-depth description of time domain theory, the reader is referred to the literature² and to the network analyzer manuals for a more detailed description of the ANA's abilities.

Basically, the problem is to take complex frequency domain data and transform it to the time domain using some form of a Fourier transform. The relationship between the frequency domain response and the time domain response is described by the Fourier transform:

$$\begin{array}{ccc} \text{Frequency domain} & & \text{Time domain} \\ H(f) & \text{---} & h(T) \end{array}$$

Coupling this information with the frequency response of the device as a function of frequency, one can obtain information on the presence, and sometimes type, of mismatches in the device as a function of distance. This can be a powerful aid in determining the location of faults and also in seeing where the various discontinuities are located in the circuit. The important thing to remember is that the frequency domain measurement is a composite response of all the discontinuities in the device, while the time domain measurement shows the effect of each individual discontinuity as a function of time and distance.

There are two modes of operation in the time domain when using the HP8510 ANA. The time domain bandpass mode is useful for measuring band-limited devices, while the time domain lowpass mode mathematically simulates the traditional type of TDR measurement and gives the user information on the type of discontinuity present, as well as its physical location in the device under test.

The bandpass mode has the advantage that there is no restriction on the frequency span of the measurement, although resolution and other factors can put a practical limit on the bandwidth of the measurement. The lowpass mode, on the other hand, is limited in its use, since the nature of the transformation requires that frequency data be taken all the way down to zero frequency, and thus restricts its use with bandpass devices. This mode gives the user some information that can be used to determine the type of discontinuity that is present, and also has the best resolution of the two modes. Some concepts of interest to any user of time domain measurement systems include the effects of masking, windowing and, most importantly, resolution. Masking is a physical phenomenon in which the response of one discontinuity affects the response of all the subsequent discontinuities in the circuit. This is a result of the fact that the power lost at each discontinuity will never reach the mismatches further on in the circuit. Windowing is a technique used to try to limit the adverse effects of the abrupt transition in the data at the start and stop frequencies. This transition introduces undesirable effects, such as overshoot and ringing in the time domain response. When this type of data is transformed to the time domain, it has a $\sin(kt)/kt$ shape, where k is a constant and t is

time. The resultant finite impulse width limits the measurement's resolution and sidelobes are introduced that further limit the dynamic range of the measurement.

Windowing essentially filters the data in the frequency domain to smooth out the abrupt transitions and, thus, can reduce the aforementioned deleterious effects. By varying the shape of the window, one can enhance the data, but a tradeoff is made. For example, sidelobes can be reduced, but a price is paid in increased impulse width.

The most important considerations are range and resolution. Range is the amount of distance one can see into the device before encountering the aliasing effects that occur for this type of discrete transformation. In other words, the nature of the transformation causes the response to be repeated at regular intervals. Range is primarily dependent on the frequency spacing of the data points. There are two kinds of resolution to be concerned with: range resolution and response resolution. Range resolution is the ability to locate a mismatch in time, or how accurately its position can be pinpointed. Response resolution is how far apart two separate discontinuities have to be in order for one to be able to see them distinctly. The response resolution is of most importance and is a function of the window shape and also inversely proportional to the frequency span of the measurement.

The feature of the transformation that is of greatest interest is the ability to filter the data in the time domain to isolate an individual response, and then transform back to the frequency domain to view the frequency response of only that response. This is a powerful tool, since theoretically one could look inside a device and observe the

frequency response of each individual response instead of the composite response.

One important aspect of looking at the time domain response of a circuit is that the response is necessarily an average over the entire bandwidth in the frequency domain. For example, any of the responses that make up the composite response for a device in the frequency domain can be singled out in the time domain, but any data taken in this mode would be an average over the frequency span. This is an important limitation, since one usually wishes to know the phase velocity as a function of frequency in the band of interest.

B. Preliminary Investigation

1. Response of Helix Circuits

a. Cold Test fixture Versus Actual Circuits

The experiments using the time domain capabilities of the HP8510 ANA were done on both actual helix circuits and special cold test fixtures. The cold test fixtures are helix circuits that are specially assembled for doing tests, such as phase velocity. Typically, the support rods in such circuits have no loss deposited on them, and the helix itself might be scaled up in diameter in order to facilitate tests, such as pulling a bead through the circuit. In addition, the helix is usually of uniform pitch. The helix circuits tested, on the other hand, are circuits that are taken from the production line and tested in situ. The rods have a loss pattern deposited on them and the helix might have a pitch taper at some point in the circuit. Most of the work was done on actual circuits; however, the work done on cold test circuits is also discussed.

b. typical response

The first thing done was to get some familiarity with what the time domain response of helix circuits looked like. A typical response is shown in Fig. 1, where the two large discontinuities are composite discontinuities that are made up of the connector and pin-to-helix connection. As can be seen in the figure, the area between these two discontinuities is essentially flat indicating no substantial mismatches along the helix length. When a bead supported on a length of nylon fishing line was inserted into the circuit, a typical response is shown in Fig. 2. This figure gives some idea of the relative magnitude of the bead response as compared to the responses of the input and output. The bead was approximately three-fourths of the helix diameter and one pitch distance wide, and was made by either putting a small amount of silver loaded epoxy on the nylon line or by gluing a small piece of metal tubing to the line.

2. Bead Tracking

The first test run was to see if the movement of the bead down the circuit could be tracked accurately. The bead was moved a known distance, and then the distance from the reference plane to the peak of the bead response was measured on the ANA. As is typical with time domain reflection measurements, the distance is the round trip distance and must also be corrected for the circuit phase velocity. The relative phase velocity (v_p/c) for this cold test circuit was 0.205. Table 1 gives the results of the tests.

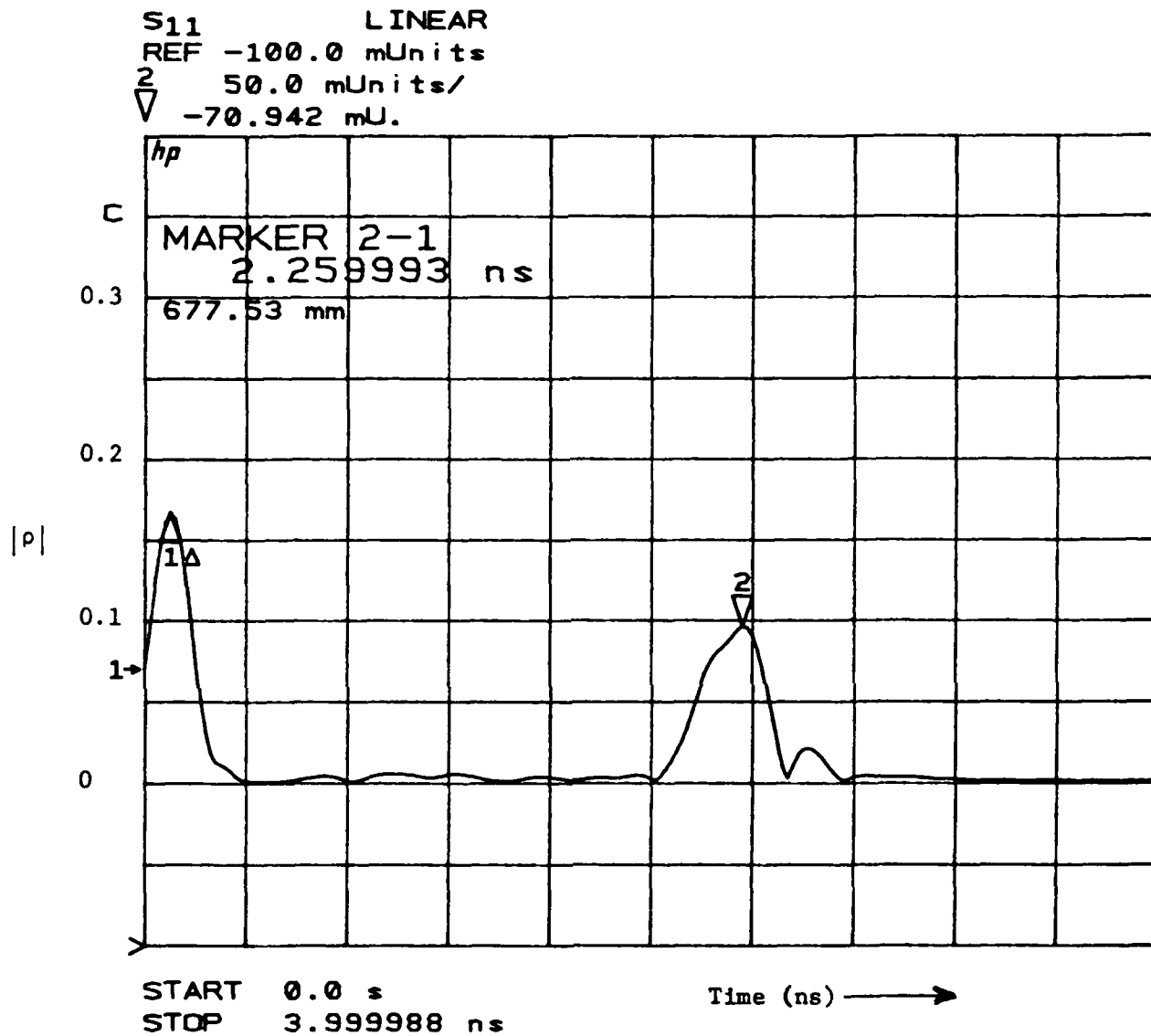


Fig. 1. A typical response of a helix cold test circuit.
 The first response is due to the input discontinuity,
 and the second to the output discontinuity.

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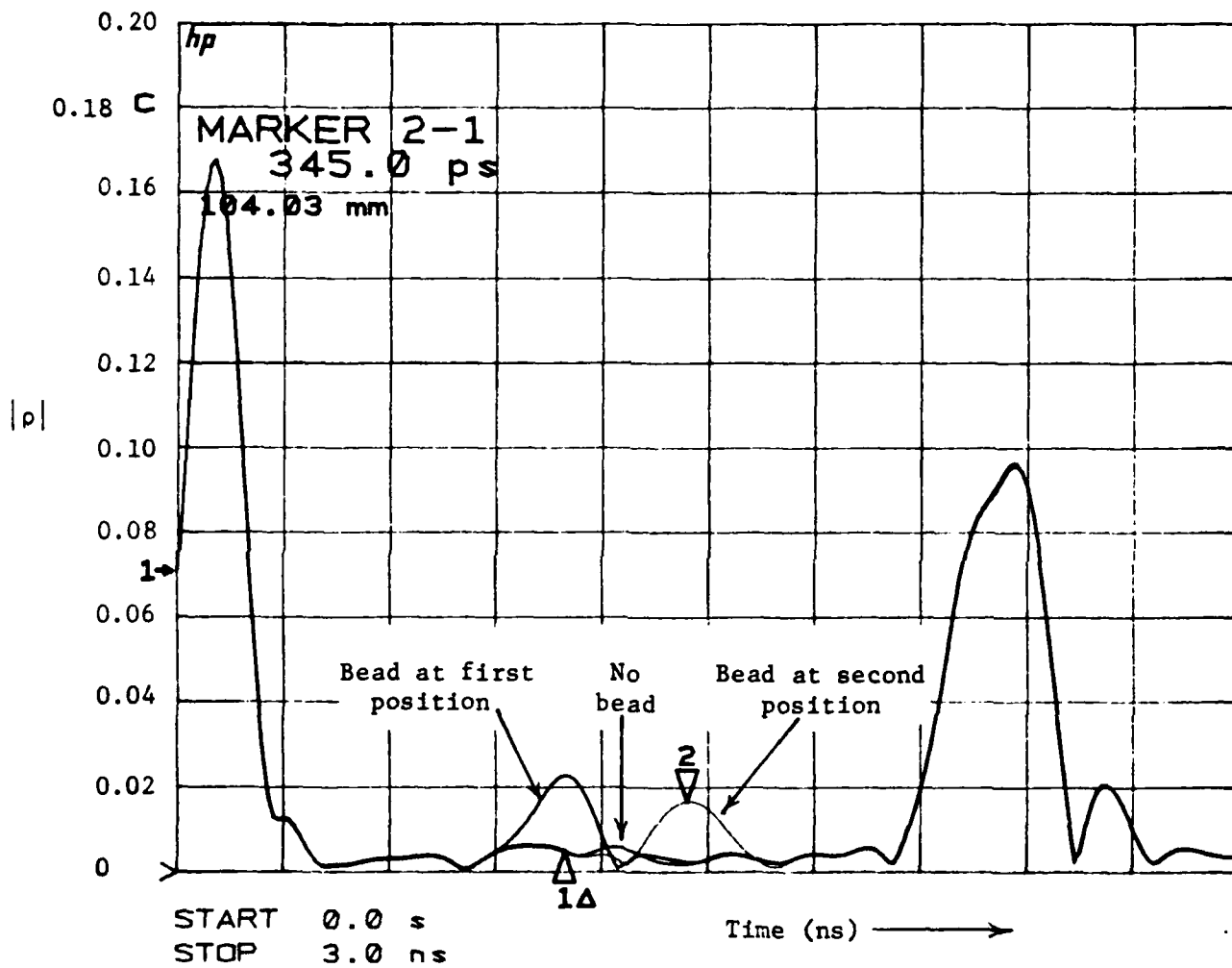


Fig. 2. The response of a helix cold test fixture with no bead, and with the bead at two different positions.

Table 1. Comparison of the physical distance moved by the bead (z column) with the value calculated from the peak of the bead's response in the time domain (delta z column). v/c was assumed to be 0.205 to make the calculations.

z(cm)	Delta z(cm)	Percent Difference
0.0	---	---
0.5	0.6038	20.76
1.0	0.5531	10.62
1.5	0.5024	0.48
2.0	0.5623	12.46
2.5	0.5670	13.40
3.0	0.5716	14.31
3.5	0.3457	-30.86
4.0	0.4794	-4.126
4.5	0.4563	-8.736

These results were not very encouraging, so another method was used. It was possible that the true position of the bead was not being accurately found. One way to try and pinpoint the position is to memorize the trace in the time domain response of the circuit without the bead present, and then subtract this response from the response when the bead is present. This way the ANA should show more accurately the difference that the bead is making to the response. However, the accuracy in the ANA's ability to track the bead was still poor, as is seen in Table 2.

Table 2. Comparison of the actual bead location to peak-of-bead response in the time domain.

z(cm)	Marker Value (cm)	Delta z (cm)	Percent Difference
0.0	1.0052	---	---
1.0	1.7245	0.7193	-28.1
2.0	2.7943	1.0698	6.98
3.0	3.9748	1.1805	18.05
4.0	5.3120	1.3373	33.73

C. Determination of v_p Versus f Using Gating

In this section, the use of gating as a tool to measure the phase velocity is investigated. The method of measurement is to insert the bead into the circuit and then transform it to the time domain. The response of the bead alone can be gated upon and then transformed back to the frequency domain. This will give the complex reflection coefficient as a function of frequency of the bead referenced to the reference plane of the network analyzer. The value of the bead's phase angle is noted, and the bead is then shifted a known distance to a new position where the process is repeated. The resultant phase shift should correlate with the circuit's phase velocity at each frequency.

This method depends on the ability of the network analyzer to precisely locate the bead within the circuit. As has already been discussed, the ANA is not accurate in this regard. Also of concern here is the quality of the filtering done in the gating process. Since the

bead's response is typically small compared with the response of the input discontinuity, if the filter is not narrow enough, some of the input discontinuities response will be included and will affect the accuracy of the data in the frequency domain. This is especially a problem at the band edges, although the data towards midband is usually unaffected unless the bead is very close to the input discontinuity.

As a check to see if this method has any merit, some tests were done on ideal circuits using the circuit modeling program (CMP) that is included with the HP8510 ANA time domain option, and also on some slotted airline.

1. Verification of Method

a. Circuit Modeling Program (Ideal Case)

The circuit modeling program is a program which can be used to compute the s parameters of ideal circuits made up of transmission lines, resistors, capacitors, and inductors. This information is then fed into the HP8510 and treated as normal data. It can then be operated on and displayed in any manner that the ANA allows. In this case, typical responses seen in the helix circuits were modeled using transmission lines, and then manipulated in order to get the frequency response of the modeled bead alone. This allows verification of the validity of the gating method for determining phase velocity. Also, it was used to observe the effect of composite discontinuities, such as those which appear in actual circuits at the input as well as what happens when the phase velocity changes along the circuit.

The first verification test was a simple cascade of a 50 ohm transmission line into a 75 ohm transmission line and back into a 50 ohm line. 9.99 GHz was arbitrarily chosen as the frequency at which to verify the method. This results in two mismatches in the time domain. What is of interest here is to see if changing the length of the 75 ohm line results in the expected behavior of the angle of the complex reflection coefficient of the second mismatch. Since the phase velocity is the speed of light, we have at 9.99 GHz,

$$\beta = 2\pi * 9.99 \text{ GHz} / 2.99e8 = 209.23 \text{ rad/meter} = 119.88^\circ/\text{cm}$$

The results of measuring the total reflection, gated first mismatch, and gated second mismatch angles are shown in Table 3. The expected shift in phase $2\beta L$ for a 0.2 cm shift in the length of the 75 Ω line is 47.952 degrees, and 119.88 degrees for a shift of 0.5 cm, using the β calculated above. From Table 3, it can be seen that the shift in phase was $107.25 - 59.25 = 47.992$ for 0.2 cm and $179.22 - 107.25 = 119.96$ for 0.5 cm. These results are well within a percent of the expected values!

Table 3. The angle of the reflection coefficient for the total circuit, the first mismatch alone, and the second mismatch alone for an ideal circuit consisting of a 50 to 75 to 50 ohm transmission line.

L(cm)	Total Reflection Angle	First Reflection Angle	Second Reflection Angle
10.0	-27.701	0.0013733	-59.258
10.2	-51.411	0.003733	-107.25
10.5	-89.58	0.0041199	-179.22

As stated above, it is also of interest to see if this method is accurate when the types of composite discontinuities seen in helix circuits are present. The response of a bead in a helix circuit was modeled by placing a composite mismatch in front of the response of the bead. It was attempted to keep the relative magnitudes close to what is actually seen in helix circuits. The time domain response of the model is shown in Fig. 3a, and the equivalent circuit shown in Fig. 3b. The length of the 76 ohm TL (simulating the shifting of the bead's response as it is moved down the circuit) was increased 0.5 cm, and the phase of the gated reflection at 9.99 GHz changed by 120 degrees as expected. This indicates that the composite response does not adversely affect the gating method in the ideal case. The last question to be addressed is the effect of changing phase velocity on the method. In an actual circuit, one would expect the region from the input window to the pin-to-helix connection to have a phase velocity roughly corresponding to coaxial line. The region after the input discontinuity will have a phase velocity characteristic of the helix itself. For this reason, another test case was run with an equivalent circuit as shown in Fig. 4. The length of 70.5 ohm TL was set to a phase velocity corresponding to the speed of light, while the 82 ohm line was given a relative phase velocity (v/c) of 0.178, which is a reasonable value for a helix circuit. The beta of the 82 ohm line is now 674.16 degrees/cm at 9.99 GHz, and thus one expects a shift of 674.16 degrees ($2\beta L$) for a shift in distance of 0.5 cm. The phase shift obtained by gating was 673.94, which is within a percent of the expected value and shows that theoretically the changing phase velocity should not affect the measurement.

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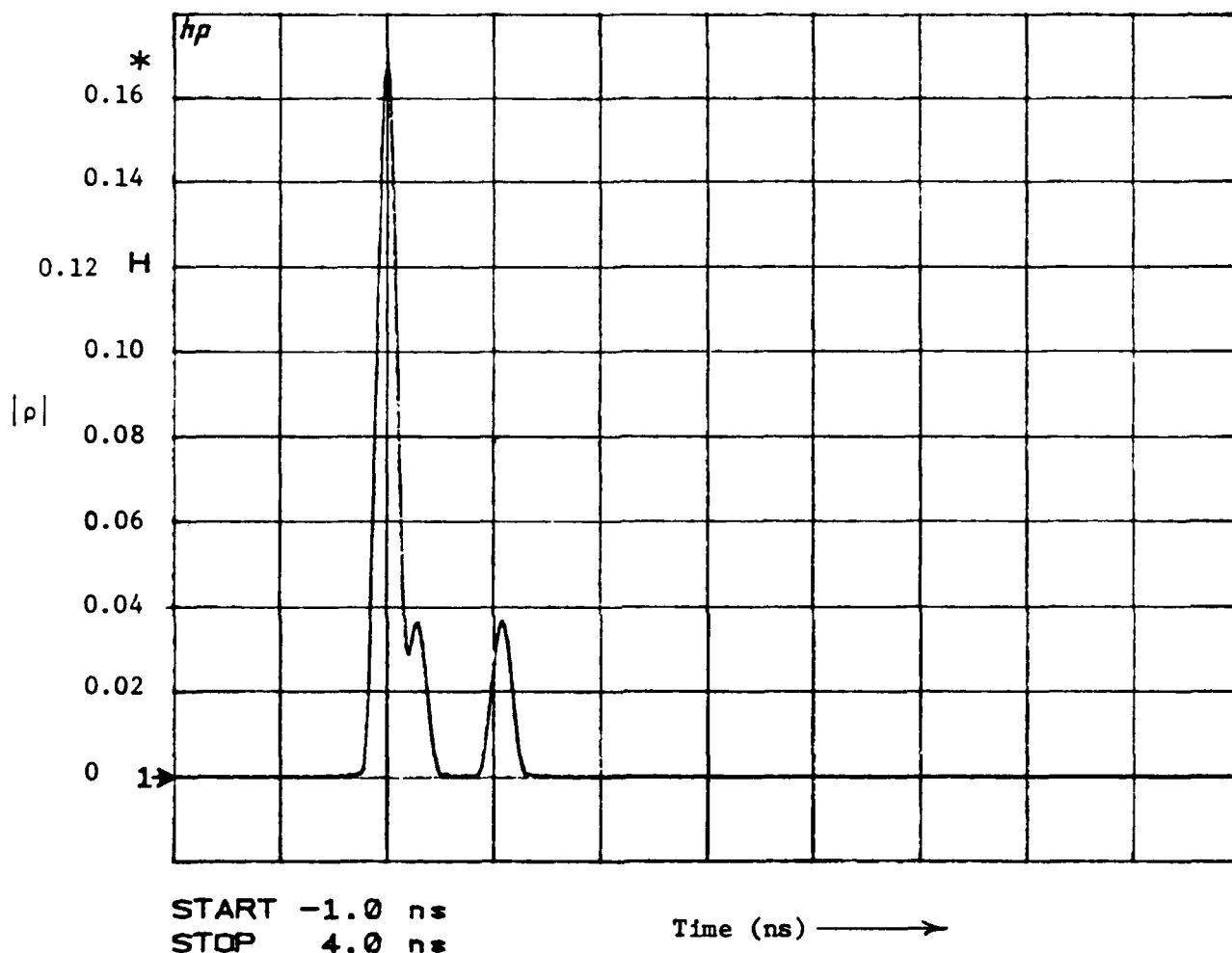


Fig. 3a. The ideal response of the circuit shown in Fig. 3b. This response is intended to model the type of response seen in helix circuits. The first response is a composite response due to the input window/helix-to-pin connection, and the last response is due to the bead.

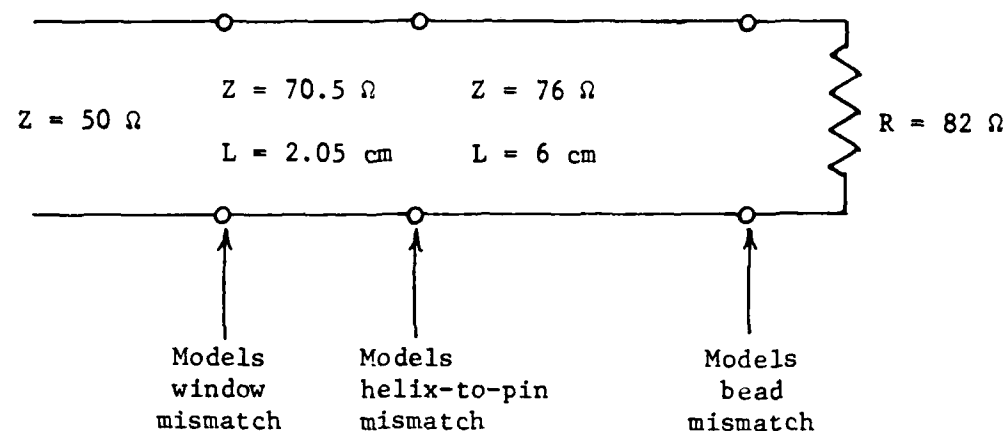


Fig. 3b. An equivalent circuit used to model the response of a helix circuit and bead.

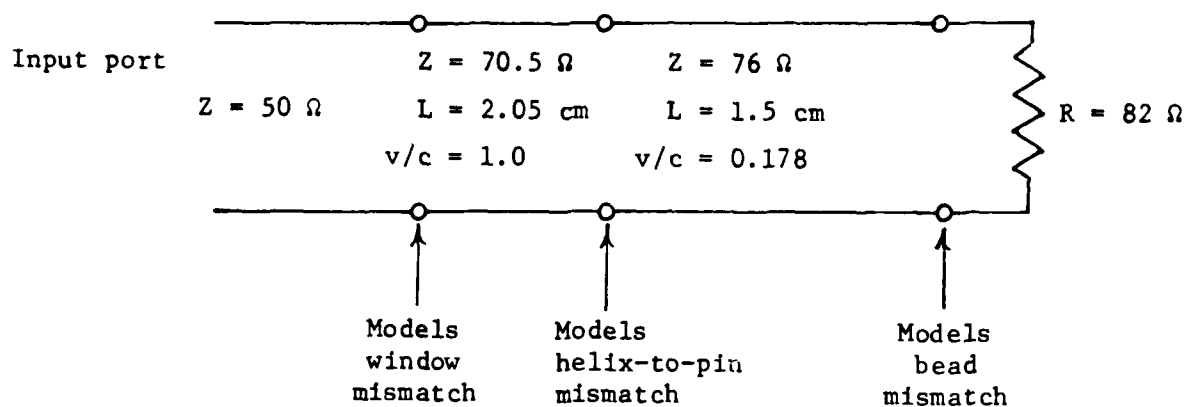


Fig. 4. An equivalent circuit used to model the helix circuit response. This circuit is used to examine the effect of varying the phase velocity at different points in the circuit.

b. Airline

Since the method seems to work properly in the ideal case, it was tried on a slotted airline fixture. This seemed to be the next step up in complexity. Two calibrations were used: Calibration 1 was from 0-22 GHz to allow for use of the lowpass mode, and Calibration 2 was from 7-17 GHz and was used in the bandpass mode of the time domain. The gating method as previously described was used, and the results are shown in Tables 4a and 4b for both calibrations. Since airline essentially

Table 4a. The phase shift resulting from several consecutive 0.5 cm shifts in the bead position at 10 GHz. The expected shift is 120 degrees.

Delta z (cm)	Cal 1: Delta ϕ (Degrees)	Cal 2: Delta ϕ (Degrees)
0.5	122.63	121.99
0.5	124.14	121.27
0.5	123.84	123.62
0.5	126.38	124.49

Table 4b. The Phase shift resulting from two consecutive 0.5 cm shifts in the bead location at 12 GHz. The expected shift is 144 degrees.

Delta z (cm)	Cal 1: Delta ϕ (Degrees)	Cal 2: Delta ϕ (Degrees)
0.5	141.19	138.31
0.5	158.82	162.68

has a normalized phase velocity of 1.0, the expected phase changes for a 0.5 cm shift at 10 GHz was again 120 degrees, while at 12 GHz the expected phase shift was 144 degrees. As can be seen in Table 4a, agreement is within 5 percent at 10 GHz for both calibrations, while from Table 4b the data at 12 GHz were not as good.

This simple test was deemed encouraging enough to have some faith in the method. The test also seemed to indicate that lowpass mode and bandpass mode give roughly the same results for this type of measurement. The next step was to try the method on some actual helix circuits.

2. Testing of Actual Circuits

The first circuit tested was a 7-17 GHz circuit with a mean diameter of 0.0723 inches and a pitch of 0.045 inches. The results of testing this circuit were not very encouraging. The response of the circuit when the bead was gated on did not give any repeatable results. The phase angles did not correlate with expected phase shifts, and also did not even shift the same in angle for the same shift in distance. The next circuit tested was at a lower frequency and, as a result, also had a larger diameter, making it easier to keep the bead centered as it was drawn down the axis. The band for which the circuit was designed was 2-8 GHz, and the mean diameter and pitch were 0.151 inches and 0.088 inches, respectively. The bead used in this case had a diameter of 0.110 inches and a width of 0.054 inches. The results of the experiment are shown plotted in Fig. 5 against data obtained for a cold test fixture made with the same circuit and tested using the resonance method discussed in Appendix C. The data are also compared numerically in Table 5.

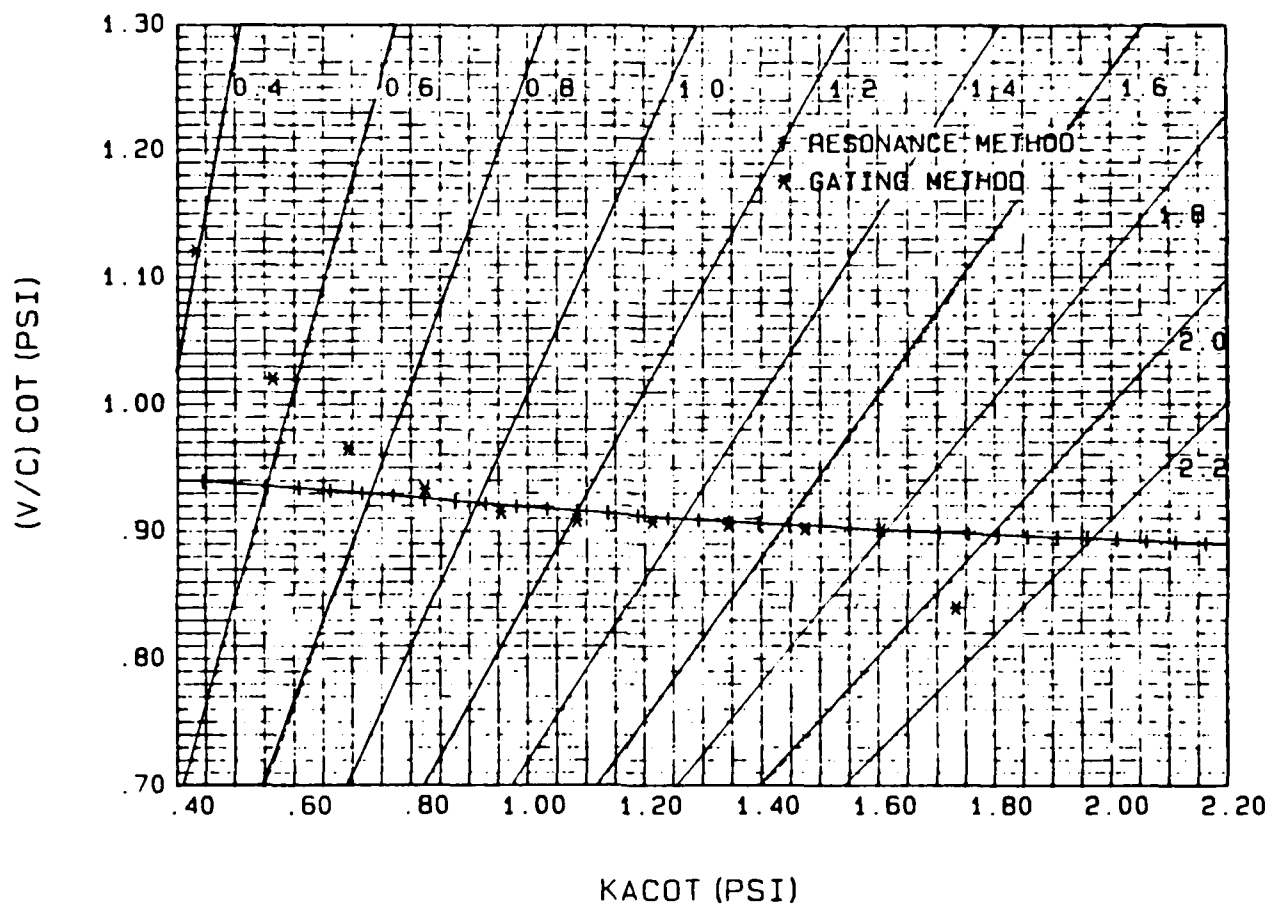


Fig. 5. Comparison of results obtained from the gating method to those obtained by the resonance method for a 2-8 GHz helix circuit. Mean diameter and pitch are 0.151" and 0.088", respectively.

Table 5. Comparison of the normalized phase velocity found using the gating method on the ANA with that found using the resonance method on a 2-8 GHz circuit

$ka \cot(\psi)$	Gating $(v/c)\cot(\psi)$	Resonance $(v/c)\cot(\psi)$	Percent Difference
0.4334	1.1205	0.9467	18.36
0.5634	1.0201	0.9402	8.50
0.6935	0.9647	0.9348	3.20
0.8235	0.9327	0.9274	0.57
0.9535	0.9152	0.9213	-0.66
1.0836	0.9080	0.9238	-1.71
1.2136	0.9074	0.9130	-0.61
1.3436	0.9058	0.9087	-0.32
1.4737	0.9019	0.9058	-0.43
1.6037	0.9004	0.8951	0.59
1.7337	0.8392	0.8973	-6.48

From the data presented, it can be seen that agreement is very good in the middle of the band, but is not good at the band edges. This type of degradation in the accuracy of the response at the band edges is related to the fact that the gating is not perfect. If the gate is not centered accurately or the span is set too wide, the frequency domain response will not be the response of the gated mismatch alone, but will also be affected by the other mismatches in the circuit. In any case, some of the effects of the rest of the circuit outside the gated region will be present. These effects tend to be more pronounced at the band edges.

D. Fault Location

The traditional application of the time domain is fault location. This can be done on helix circuits quite easily with the ANA. Being able to locate the general position of a discontinuity in a TWT can be a great help in analyzing a possible failure due to an opened pin-to-helix connection, melted circuit, etc. Usually, a tube must be opened up to examine the circuit in order to determine the failure mechanism. TDR can give the user some idea of what may have happened without opening the tube.

The best way to implement this type of use for TDR would be to plot the time domain response of each circuit before it is aged and tested. Then, if a problem like a melted helix is suspected, the time domain response could quickly be plotted again, and any significant changes noted. Although the location of a discontinuity cannot be determined exactly, as was discussed in the section on bead tracking, a general idea of its location is obtained. In these types of failures, the location is not as important as whether or not they are present.

An open pin-to-helix connection is illustrated in Fig. 6, where it is quite obvious what has happened, since the response of the circuit before the open occurred is known. As would be expected, there is a dramatic change in the time domain response. An open helix was not actually tested, but was simulated by placing a metal rod in the circuit to create a substantial mismatch. Figure 7 shows what might be seen if the helix was melted somewhere down its length. From this plot, it would be easily seen that the problem is not at the input, as in the

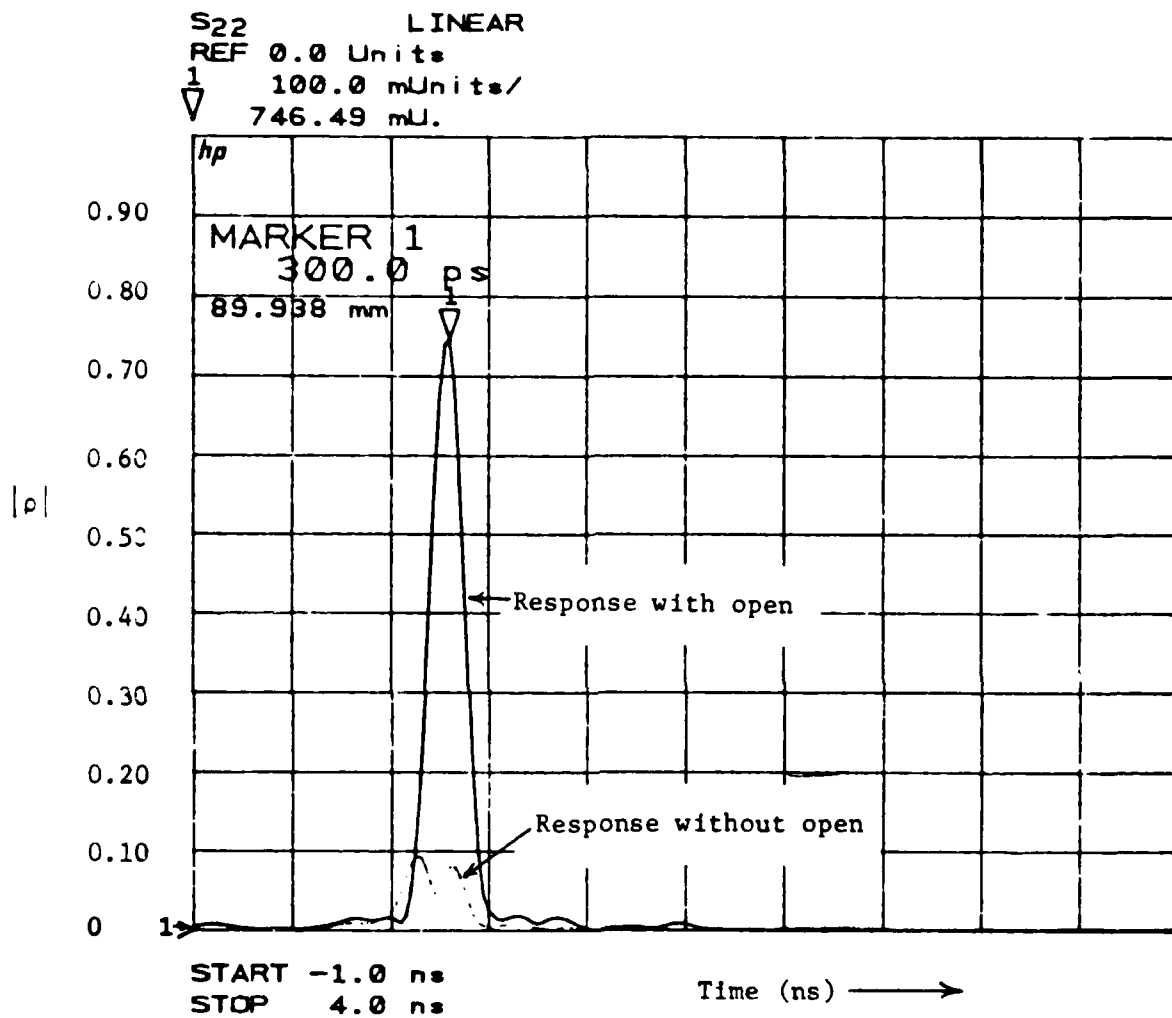


Fig. 6. The response of a circuit with an opened helix-to-pin connection, as well as the response before the open occurred.

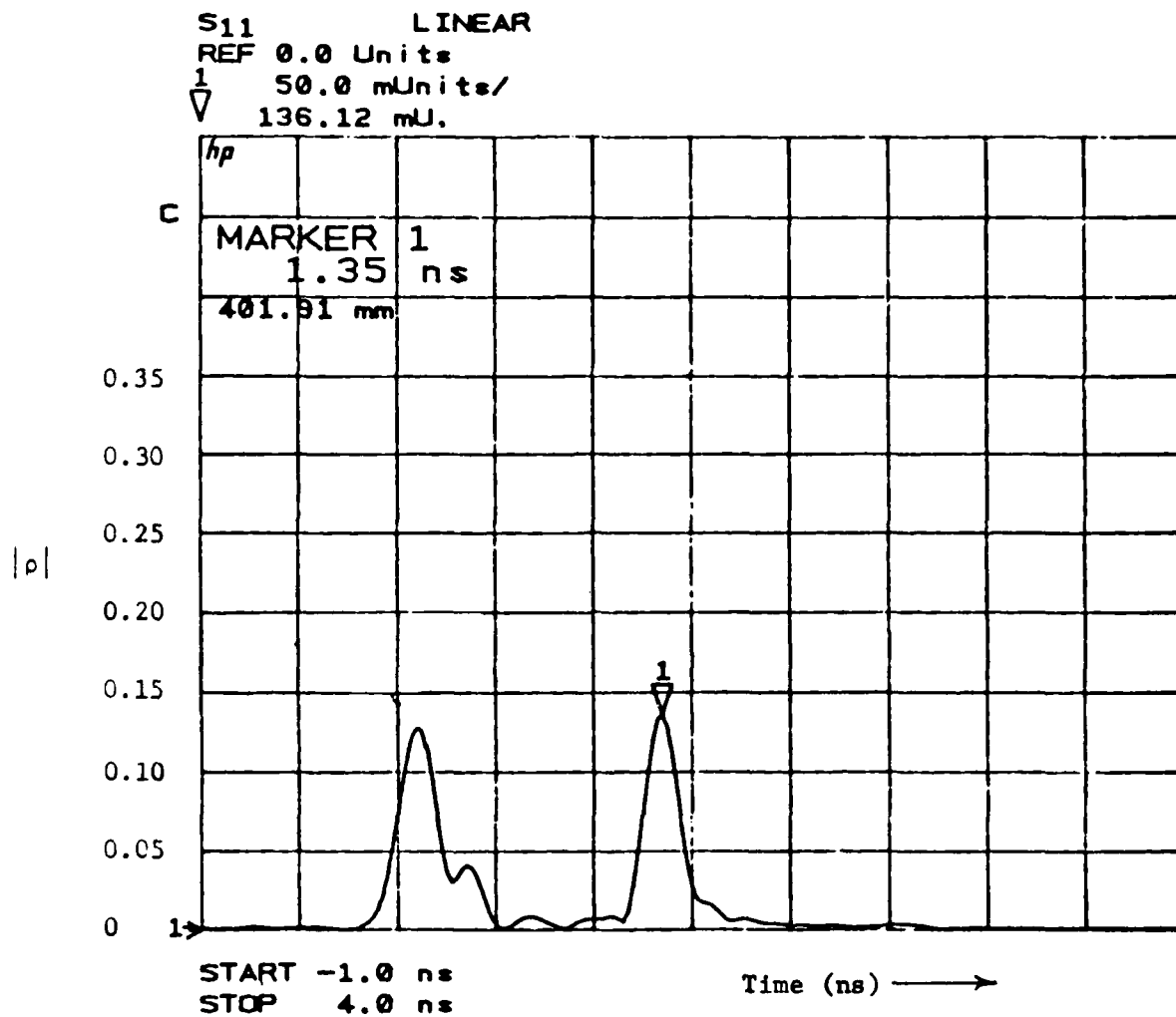


Fig. 7. A melted (opened) helix approximately one inch past the input connection in the time domain.

preceding case, but approximately 1.3 inches ($v/c = 0.17$ for this circuit) down the length of the helix.

The ability to see problems on the circuit is, of course, limited by the amount of loss and how dramatic a mismatch is present. However, the ease with which tests of this nature can be done makes the TDR capabilities of an ANA viable as a quick check on the presence of potential circuit problems.

IV. FREQUENCY DOMAIN MEASUREMENTS

A. General Theory

In this section, the concern is to get accurate phase velocity data utilizing the vector nature of the data itself without having to utilize the time domain capabilities of the network analyzer. This has been done by some researchers already, as reported in the literature,³ however, the actual calculations involved are often left to the reader. It is the purpose of the author to include all the necessary information to allow the utilization of this method to any one with access to a vector ANA and a computer.

B. Automation of Measurements and Calculations

This method is based on a two-boundary reflection model, which is discussed in Appendix A. The method of measurement is much simpler than the method used in the time domain measurements. The first thing done is to measure the swept complex reflection of the helix circuit. At this point, the circuits used are actual circuits with loss, as this is what the model was designed for. Without the bead in the circuit, it is assumed that the resultant reflection is due entirely to the input discontinuity, and that there are no reflections further down the tube or that they are hidden by the loss pattern on the rods. The bead is then introduced, which creates the second mismatch that is included in the model. The bead is moved at regularly spaced intervals along the circuit, with swept data being taken at each position. These data are read from the ANA and dumped to a floppy disc using a data acquisition program on a Hewlett Packard series 200 PC. The data are then read into

an HP1000 computer which has the model program on it. The whole process could, of course, be done completely on either of the two computers. Both programs are discussed in Appendix B.

The output of the program at one frequency is shown in Fig. 8. The program prints out the phase shift for each position of the bead, the corresponding phase constant, and the normalized phase velocity. Next, an average of each of these quantities is printed along with normalized frequency ($ka \cot(\psi)$), normalized phase velocity $[(v/c)\cot(\psi)]$, and the high and low values of the phase shift and normalized phase velocity. The data were generally taken within a uniform length of the helix circuit, which is the reason for averaging the data over the whole length. The data could, however, be taken over a length of circuit that includes a pitch taper, in which case the computer code gives an indication of the phase velocity as a function of distance along the circuit. In this case, the averaging of the data at the end of the output is meaningless. The data were taken in the relatively loss-free area of the circuits tested, i.e., in the "clean length," in order to get the best accuracy out of the model.

C. Comparison of Results with Known Phase Data

The first circuit tested had a mean diameter of 0.1274 inches and a pitch of 0.028 inches, and was designed for operation in the 2-8 GHz band. This size circuit tended to be the easiest to do measurements on, as it was much easier to get the bead centered and also to make a bead that was not too large for the circuit. The bead size used in this case was 0.032 inches wide with a diameter of 0.049 inches. The data were

Freq = 7.40 GHz

<u>Phi(deg)</u>	<u>Beta(deg/cm)</u>	<u>v/c</u>
107.806	539.03	.16529
104.815	524.07	.17001
103.545	517.73	.17209
106.607	533.04	.16715
109.024	545.12	.16345
109.395	546.98	.16289
110.708	553.54	.16096
105.341	526.70	.16916
111.681	558.40	.15956
107.973	539.87	.16504
103.695	518.47	.17184
107.545	537.73	.16569
107.635	538.18	.16555

Phi ave. = 107.367

Beta ave. = 536.83

v/c ave. = .16605

kacot(psi) = 3.2074

(v/c)cot(psi) = .8951

Phi varies by 4.0%(111.68) and -3.6%(103.55).

Vrel varies by -3.9%(.1596) and 3.6%(.1721).

Fig. 8. An example of the output from the REFEQ program at one frequency.

taken in ramp mode, in which the source is swept in a continuous analog sweep from the lower to upper frequency without stopping the sweep. The ANA can also be operated in step mode, where it stops at each frequency point and phase locks to each point. This is more accurate, but much slower and does not seem to affect the results of the measurements done here.

The results of running the program REFEQ on the data for the circuit are shown in Table 6. The table shows the average phase

Table 6. The results of running the program REFEQ for the first circuit tested. The average phase constant, normalized phase velocity, and variation in the results are shown.

f(GHz)	Average β (°cm)	Average v/c	Variation from Mean in Data for v/c
2.0	346.82	0.06948	+2.6, -4.3%
2.6	456.13	0.06872	+4.6, -4.9%
3.2	565.99	0.06815	+5.5, -4.6%
3.8	682.23	0.06709	+3.2, -3.9%
4.4	789.97	0.06711	+3.5, -4.3%
5.0	896.06	0.06721	+2.7, -3.4%
5.6	1011.0	0.06671	+3.1, -3.6%
6.2	1101.5	0.06782	+3.3, -4.1%
6.8	1216.7	0.06736	+5.4, -5.5%
7.4	1318.8	0.06769	+8.7, -5.9%
8.0	1419.3	0.06816	+8.4, -8.5%

constant, the normalized phase velocity (v/c), and the amount of variation in the data for the normalized phase velocity at each frequency. The bead was shifted at regular intervals of 0.2 cm. In Fig. 9, the data are normalized to the circuit diameter and pitch as normalized frequency $[ka \cot(\psi)]$ and normalized phase velocity $[(v/c)\cot(\psi)]$, where $\cot(\psi) = \pi * \text{diameter/pitch}$, and the resultant data are plotted against the data for the same circuit obtained by the scalar bead pull method described in Appendix C. As can be seen, the agreement is quite good over the portion of the band for which comparison data were available. Table 7 compares the data at the three points of the vector ANA data that fall close to scalar bead pull data points. The data for the two methods are within 2 percent of each other, which is very good agreement.

Table 7. Comparison of the results obtained using the ANA to calculate normalized phase velocity with that obtained using the beam pull method.

$ka \cot(\psi)$	HP8510 $(v/c)\cot(\psi)$	Bead Pull $(v/c)\cot(\psi)$	Percent Difference
1.0704	0.9051	0.8981	-0.773
1.3175	0.8977	0.8885	-1.030
1.5645	0.8837	0.8922	0.962

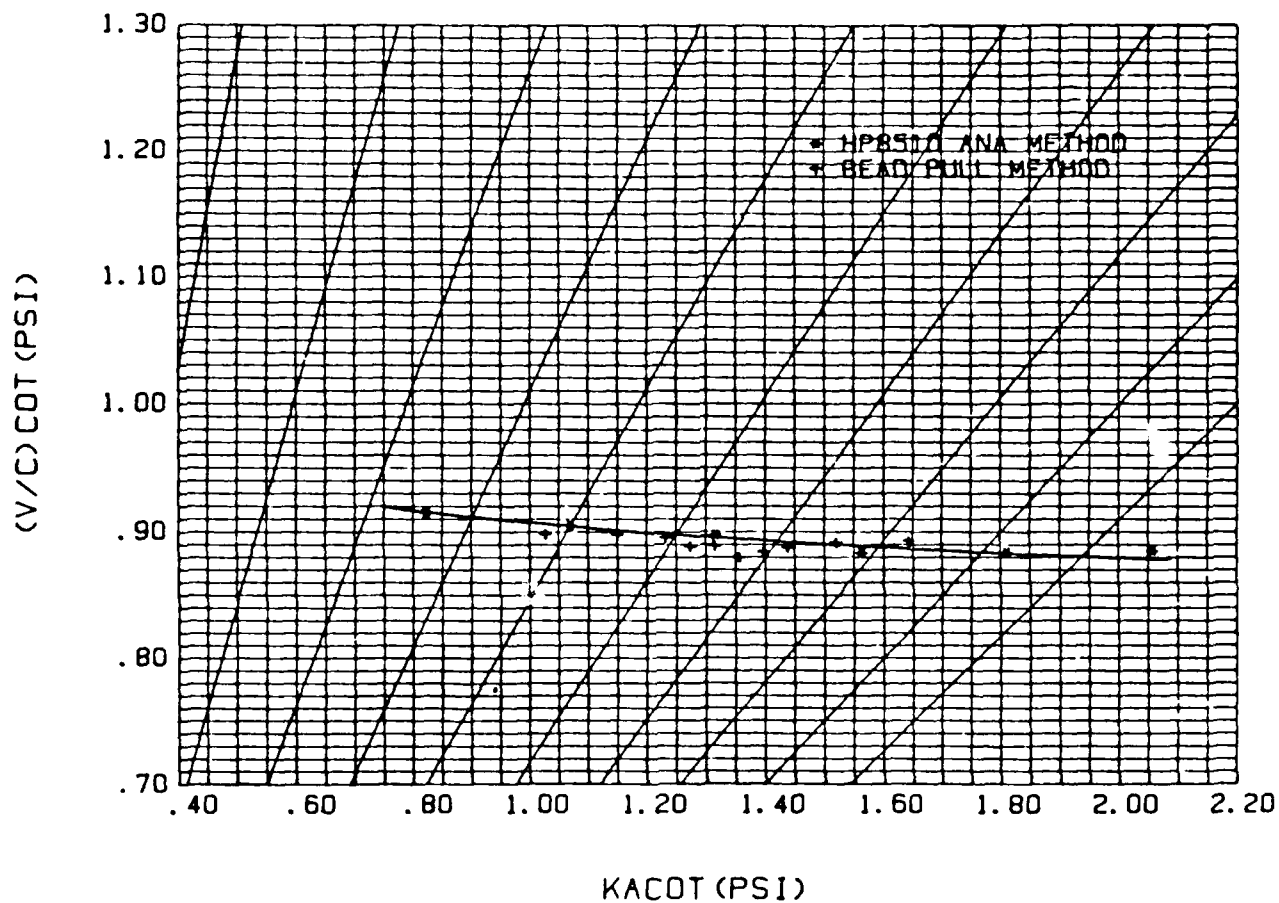


Fig. 9. Comparison of results obtained using the REFECQ program with those obtained by the bead pull method. Circuit mean diameter is 0.1174 and pitch is 0.028.

The next circuit tested was the same circuit that was tested in the time domain section for 2-8 GHz. The mean diameter was 0.151 inches and the pitch was 0.088 inches. The average results of running REFEQ on the data are shown in Table 8. The normalized phase data are compared

Table 8. The results of running the program REFEQ for the second circuit tested. The average phase constant, normalized phase velocity, and variation in the results are shown.

f(GHz)	Average β (°cm)	Average v/c	Variation from Man in Data for v/c
2.0	137.21	0.17561	+3.4, -5.1%
2.6	179.55	0.17441	+3.2, -3.1%
3.2	222.28	0.17340	+3.2, -3.9%
3.8	266.08	0.17203	+3.1, -4.3%
4.4	311.49	0.17090	+12.4, -9.3%
5.0	352.55	0.17137	+10.0, -8.1%
5.6	398.33	0.16936	+4.6, -3.9%
6.2	443.14	0.16857	+4.0, -3.8%
6.8	487.61	0.16804	+4.2, -3.6%
7.4	536.83	0.16605	+3.6, -3.9%
8.0	579.18	0.16646	+4.8, -3.8%

to the expected results in Fig. 10. In this case, the comparison data were obtained using the resonance method, in which case a cold test circuit was used with no loss pattern, as discussed in Appendix C. As can be seen from Fig. 10, the agreement looks very good. The points are compared numerically in Table 9 and are seen to vary by less than 1 percent from each other.

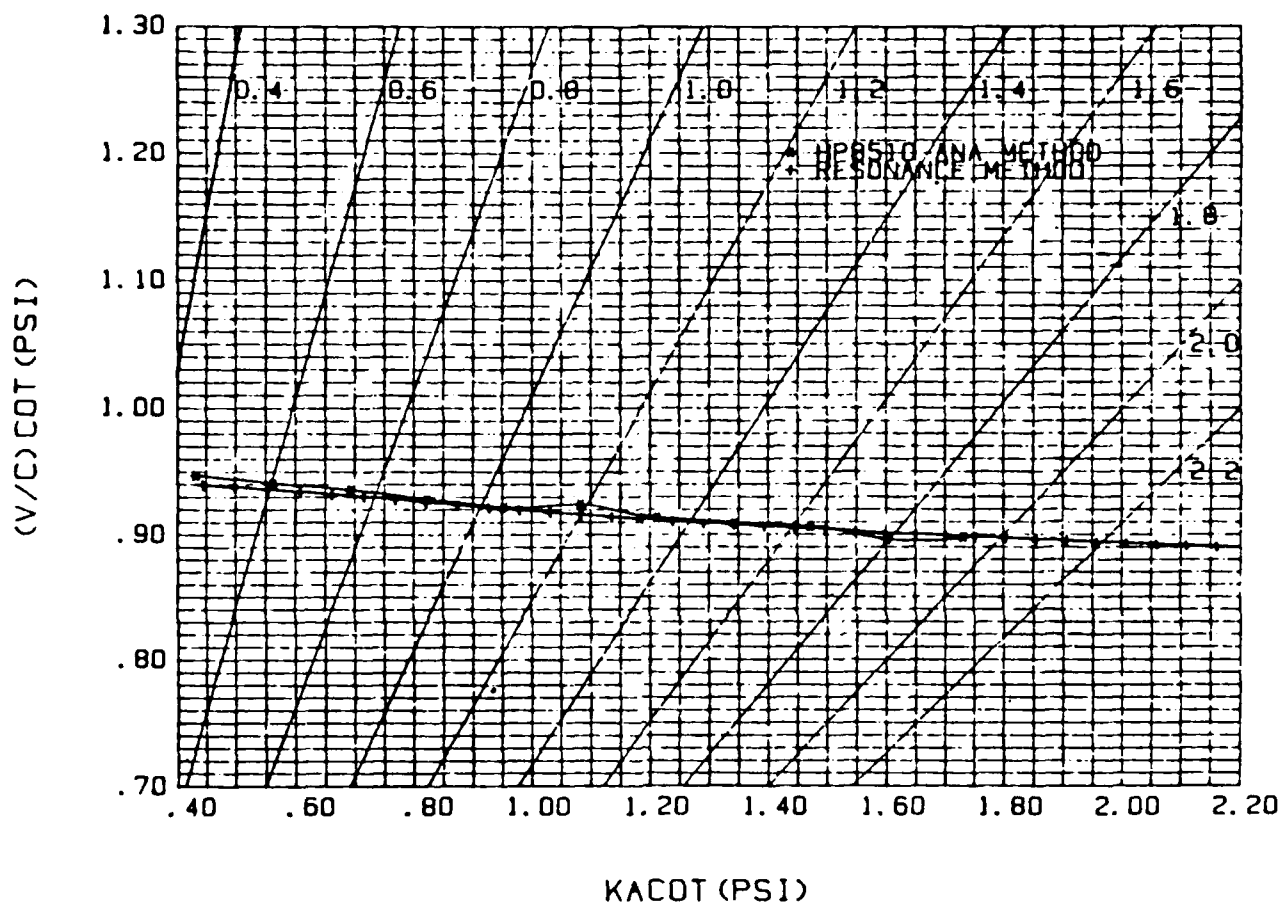


Fig. 10. Comparison of results obtained for a second circuit tested using the program REFEQ with those obtained using the resonance method. Circuit diameter and pitch are 0.151" and 0.088", respectively.

Table 9. Comparison of the results obtained using the ANA to calculate normalized phase velocity with that obtained using the resonance method for the second 2-8 GHz circuit tested

$ka \cot(\psi)$	HP8510 $(v/c)\cot(\psi)$	Resonance $(v/c)\cot(\psi)$	Percent Difference
0.5635	0.9402	0.9350	-0.553
0.6935	0.9348	0.9305	-0.460
0.8235	0.9274	0.9254	-0.216
0.9535	0.9213	0.9203	-0.109
1.0836	0.9238	0.9156	-0.888
1.2136	0.9130	0.9111	-0.208
1.3436	0.9087	0.9072	-0.165
1.4737	0.9058	0.9042	-0.177
1.6037	0.8951	0.9006	0.614
1.7337	0.8973	0.8979	0.067

The last circuit tested was the IJ band circuit that was also tested in the time domain portion of this paper. The results of calculating the phase velocity using this method were not much more encouraging than the results found using the gating method described above. Figure 11 shows the comparison of the data taken to the expected data. The bead pull data are what are expected and, as can be seen in the figure, the data obtained here are quite far off at the high end.

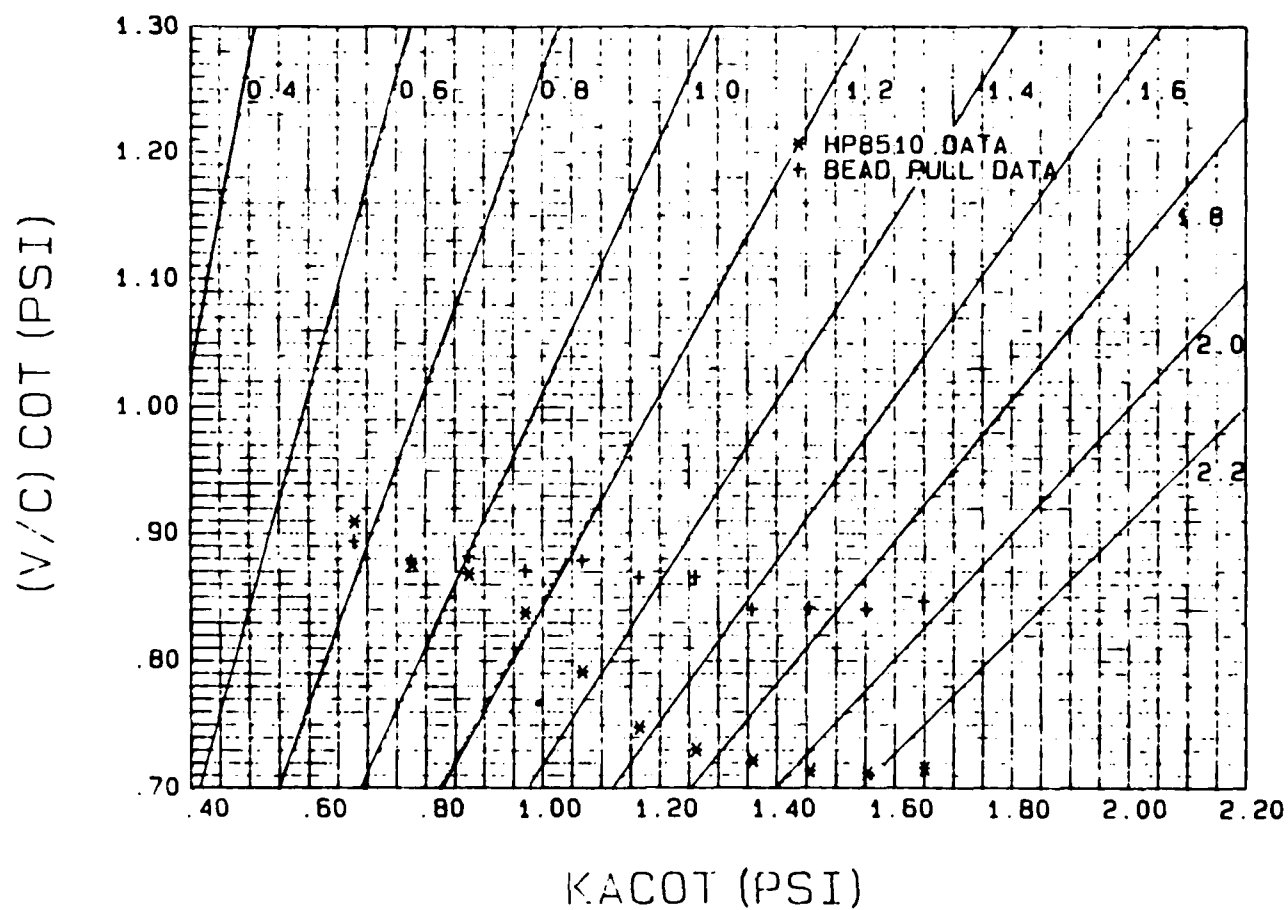


Fig. 11. Comparison of results for the IJ band circuit obtained using the REFEQ program with those obtained using the bead pull method. Circuit mean diameter and pitch are 0.0723" and 0.045", respectively.

V. CONCLUSION

The results of the experiments in the time domain indicated that precisely locating the position of the bead in the circuit was not possible. However, when using the gating method of determining a circuit's phase velocity, good results were obtained for the 2-8 GHz circuit. This indicates that although the gating filter could not be centered exactly on the bead's response, the major portion of the bead's response was still included within the filter, resulting in the expected results for the center of the frequency band. The degradation in the accuracy of the data obtained by this method at the band edges can be attributed to this inability to precisely locate the gating filter on the bead's response. When attempting to utilize this method on an IJ band circuit, no reasonable results were obtained. Increasing the resolution in the time domain by increasing the frequency span of the measurements did not result in any improvement in the data in this case. The tests were run using both bandpass and the greater resolution lowpass modes.

The traditional use of TDR, namely the locating of faults as a function of distance, has proved to have some use in helix circuits as a quick check on the condition of a circuit in a failed tube without having to open a vacuum seal. Comparing the time domain response of a failed tube with its original response can show quite readily the existence of such failure mechanisms as opened pin-to-helix connections and melted helices.

The method of obtaining phase velocity by exploiting the complex nature of the reflection data obtained on a vector NA proved to be the more accurate of the two methods. Although both methods gave good results when used on the 2-8 GHz circuits, the frequency domain method gave accurate results over the entire band of interest, while the time domain gating method did not. The frequency domain method is more computationally intensive than the gating method, but would also lend itself more easily to total automation of the measurement process, which is a great advantage.

The failure of either method to achieve any significant amount of accuracy for the IJ band circuits tested was disappointing. One possible reason for this is that the size of the circuits was much smaller for the IJ band circuits than for the other circuits tested. This made it harder to construct beads for these circuits and also to get the bead centered on the axis of the circuit. Also, the match of the IJ band circuit tested was not as good as the match of the other circuits tested, which causes the masking affects to be more serious in the time domain.

All in all, it is the opinion of the author that the HP8510 and, in general, any time domain capable vector network analyzer can be of value in the testing and design of helix tubes. The phase velocity measurement methods described herein are quick and simple to run once they have been implemented and, thus, would allow phase velocity measurements to be done on each circuit coming off the line to give some idea how the tube will behave in test. And, as stated above, the ANA is

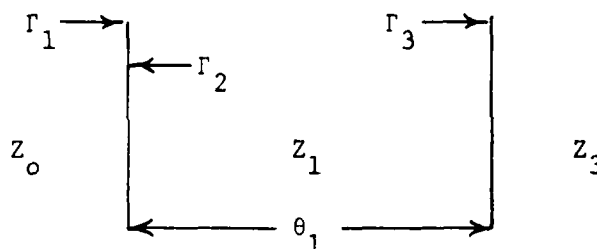
also of value in determining the failure mechanism in a bad tube without having to open the vacuum envelope.

Some areas for further research would be the implementation of a loss versus distance and impedance method using this piece of equipment. With the addition of these abilities, the usefulness of the ANA in the tube industry would be enormous.

APPENDIX A

DERIVATION OF PHASE VELOCITY MODEL FOR FREQUENCY DOMAIN

The model used for the calculation of the phase velocity was a two-boundary system. The circuit was assumed to have only a single discontinuity at the input to the helix due to the good match achieved further down the circuit as a result of the loss pattern. The bead, when inserted into the circuit, is assumed to be the only other mismatch. The quantity of interest is then the phase angle between these two mismatches. A diagram of the model is shown below.



This sort of system is analyzed in most basic EM books.* Assuming that

$$\Gamma_2 = -\Gamma_1$$

the total reflection for the system is

$$\Gamma_t = \frac{\Gamma_1 + \Gamma_3 e^{-j2\theta}}{1 + \Gamma_1 \Gamma_3 e^{-j2\theta}} \quad (\text{A.1})$$

Assuming second-order terms to be small, Eq. A.1 becomes

$$\Gamma_t = \Gamma_1 + \Gamma_3 e^{-j2\theta}$$

Now, if one considers the system: (1) with the second boundary removed, (2) with the mismatches an arbitrary phase angle θ_1 apart, and (3) with the mismatches an additional arbitrary distance θ_2 apart, the following equations result:

$$\Gamma_{tI} = \Gamma_1 \quad (A.2)$$

$$\Gamma_{tII} = \Gamma_1 + \Gamma_3 e^{-j2\theta_1} \quad (A.3)$$

$$\Gamma_{tIII} = \Gamma_1 + \Gamma_3 e^{-j2(\theta_1 + \theta_2)} \quad (A.4)$$

Substituting Eq. A.2 into Eqs. A.3 and A.4 leads to

$$\Gamma_{tII} - \Gamma_{tI} = \Gamma_3 e^{-j2\theta_1}$$

$$\Gamma_{tIII} - \Gamma_{tI} = \Gamma_3 e^{-j2(\theta_1 + \theta_2)}$$

Eliminating Γ_3 yields

$$\frac{\Gamma_{tIII} - \Gamma_{tI}}{\Gamma_{tII} - \Gamma_{tI}} = e^{-j2\theta_2} \quad (A.5)$$

and from Eq. A.5, it can be seen that

$$\theta_2 = -\frac{1}{2} \text{ ANG} \left[\frac{\Gamma_{tIII} - \Gamma_{tI}}{\Gamma_{tII} - \Gamma_{tI}} \right]$$

For the exact case, one has

$$\theta_2 = -\frac{1}{2} \text{ ANG} \left[\frac{(\Gamma_{tIII} - \Gamma_{tI})(1 - \Gamma_{tI}\Gamma_{tII})}{(\Gamma_{tII} - \Gamma_{tI})(1 - \Gamma_{tI}\Gamma_{tIII})} \right]$$

APPENDIX B

COMPUTER PROGRAMS

1. Use of Programs

a. Data Acquisition Program

This program is used to read data from the HP8510 and dump it to a floppy disc for transfer to the HP1000 computer. The program is in basic and runs on the series 200 HP computer. The program prompts the user for a header to write on the first line of each file written on the disc. It then waits for the user to press the continue key when ready to transfer data, i.e., when the bead has been moved to a new position. The program then asks for the name of the data file to be created. Each time the all data are dumped to the disc, the data go into a new file. These files must be named using single or double letters in alphabetical order, i.e., a,b,c,..., or aa,bb,cc,..., in order to use the sorting routine included in the REFEQ program. The program assumes a 51 point trace. Each file on the disc contains a header, the start and stop frequencies, and then the trace data in ascending order.

b. REFEQ Phase Velocity Program

This program is used to analyze the data taken on the ANA by reading the files created by the data acquisition program. This code is written in Fortran. It can sort the data from the floppy disc to create the necessary input file, or use an already existing file.

The input file used by REFEC is illustrated in Fig. B.1, which shows the necessary format of the input file. The first line is a header which can be anything, and usually contains circuit information, date, etc. The second line contains the mean circuit diameter in inches and the value of $\cot(\psi)$. The next line starts the first group of reflection data for a given frequency. Figure 7 shows a frequency of 2.6 GHz (first item on line). The next item on the line is read as the variable N and tells the program how many times it will calculate the phase velocity for the given frequency. This number must be one more than the desired number of times the phase velocity is to be calculated. In this case, the 19 means that the phase velocity will be calculated 18 times. Also, there must be N+1 lines of reflection data between this line and the next line containing an integer. The last variable read on this line is the delta z, the amount that the bead was moved each time, in centimeters. The next line, line 4, contains the complex reflection of the circuit without the bead present. The third number on this line is an offset that allows the user to add a constant multiple of 180 degrees to the result of the code's phase angle calculation. This is for cases when the distance that the bead is shifted results in a phase shift greater than 180 degrees, since the functions used in the code can only give results between ± 180 degrees. The next N lines are complex reflection data for the bead at each subsequent position followed by the offset. After reading these values, the program wants to read N again, and if it is zero, the code is ready to go to the next set of frequency data. If it is nonzero, the computer will expect to read N more lines of reflection data. This is used if the data taken

```

6/20/87 DATA ON 611
.151 5.3907
2.6 19 .2
-.41359E-01 .23746E+00 0
-.43419E-01 .22393E+00 0
-.54878E-01 .23413E+00 0
-.48615E-01 .24855E+00 0
-.33783E-01 .24741E+00 0
-.29503E-01 .23290E+00 0
-.41977E-01 .22444E+00 0
-.54481E-01 .23339E+00 0
-.49057E-01 .24847E+00 0
-.33249E-01 .24758E+00 0
-.29076E-01 .23228E+00 0
-.42137E-01 .22446E+00 0
-.54359E-01 .23405E+00 0
-.48294E-01 .24839E+00 0
-.33524E-01 .24694E+00 0
-.29983E-01 .23272E+00 0
-.42595E-01 .22472E+00 0
-.54222E-01 .23400E+00 0
-.49156E-01 .24873E+00 0
-.32448E-01 .24740E+00 0
0
3.2 19 .2
.21046E+00 .10998E+00 0
.19534E+00 .11162E+00 0
.21004E+00 .12516E+00 0
.22467E+00 .11091E+00 0
.21085E+00 .95924E-01 0
.19638E+00 .10899E+00 0
.20870E+00 .12405E+00 0
.22462E+00 .11275E+00 0
.21236E+00 .95917E-01 0
.19576E+00 .10812E+00 0
.20840E+00 .12492E+00 0
.22478E+00 .11273E+00 0
.21303E+00 .95535E-01 0
.
.
.
.
.
-.14399E+00 .16364E+00 0
-.14075E+00 .14677E+00 0
-.12526E+00 .15975E+00 0
0
0 0 0 0

```

Fig. B.1. Example of input data file for REFEQ program.

are not evenly spaced and can be used to exclude data that are obviously bad. At the end of the data file, four zeros tell the code there are no more data.

The program, when run, will ask the user if it is to create an input file from data on the disc. If so, the program asks for the number of files to be processed and whether they have single letter or double letter names. It then prompts for the name of the input file to be created, the title line for the file, the helix radius, and the value of $\cot(\psi)$. If the user does not wish to create an input file, but wishes to use an already existing one, the code prompts for the name of the input file to be used, and whether the reflection data in the file are in polar or cartesian form. Next, the code asks for the name of the output file to be used and the plot output file. Giving a zero for the plot file name causes no plot file to be used. Finally, the code prompts the user to input whether to use the exact model or the small signal model.

2. Data Acquisition Code Listing

```

1  REMISION OF RET 05/11.87 RET4b
10  THIS PROGRAM WILL RETRIEVE S PARAMETER DATA FROM THE
20  IMP 2510 ANA AND WRITE THAT DATA TO A DISK FILE.
30  THE PROGRAM ASSUMES THAT YOU ARE USING A 51 POINT CALIBRATION
40  ASSIGN @Hp_1b TO 7
50  ASSIGN @Nwa TO 716
60  AEORT @Hp_1b
70  CLEAR @Hp_1b
80  REMOTE @Hp_1b
90  REMOTE @Nwa
100  DIM Headers$(60),File_names$(10),B$(2)
110  DIM S11(50,1)
111  OUTPUT @Nwa:"DEBUOFF:"
113  OUTPUT @Nwa:"CONT"
114  BEEP
120  INPUT "HEADER?(TITLE, DATE, ECT.,NO COMMAS,80 CHAR MAX,50 DISPLAYED ON 85)
121  OUTPUT @Nwa:"ENTO:"
130  OUTPUT @Nwa:"TITL***:Headers$:"***:"
131  PRINT Headers$
134  BEEP
135  OUTPUT @Nwa:"ENTO:"
137  LOCAL @Nwa
138  DISP "PRESS Continue WHEN READY TO TRANSFER DATA"
139  PAUSE
141  DISP "MEASURING DEVICE"
145  REMOTE @Nwa
150  IFIND THE START AND STOP FREQUENCIES
160  OUTPUT @Nwa:"FORM4: STAR: OUTPACTI:"
170  ENTER @Nwa:Start_freq
171  PRINT Start_freq
180  OUTPUT @Nwa:"STOP:OUTPACTI:"
190  ENTER @Nwa:Stop_freq
191  PRINT Stop_freq
200  OUTPUT @Nwa:"S11: NUM61: FORM4: OUTPDATA:"
210  ENTER @Nwa:S11(*)
340  OUTPUT @Nwa:"ENTO:"
350  LOCAL @Nwa
360  CLEAR @Hp_1b
370  STORE S11 ON DISK WITH HEADER AND FLAG
380  THE FLAG "T" SHALL BE USED.
391  BEEP
392  BEEP
400  INPUT "FILE NAME?",File_names$
410  CREATE ASCII File_names$,25
420  ASSIGN @Path TO File_names$;FORMAT ON
430  OUTPUT @Path:"T",Headers$,Start_freq,Stop_freq,51,S11(*)
440  ASSIGN @Path TO *
441  PRINT File_names$
443  GOTO 40
444  INPUT "FILE NAME?",File_names$
445  ASSIGN @Path TO File_names$;FORMAT ON
446  ENTER @Path:B$,Headers$,Start_freq,Stop_freq,Num,S11(*)
447  ASSIGN @Path TO *
448  FOR I=0 TO 50 STEP 5
449    PRINT Start_freq+I*(Stop_freq-Start_freq)/50,
450    FOR J=0 TO 1
451      PRINT S11(I,J),
452    NEXT J
453    PRINT
454  NEXT I
455  END

```

3. Phase Velocity Code Listing

Page 1 FTN.

Opts: 77/LYIS

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```

1 $FILES(3,3)
2     PROGRAM REFEG
3 C*****
4 C*****
5 C*
6 C* This program uses reflection data in polar form (as per HP8510)
7 C* to solve for the phase change between two positions of the per-
8 C* turbing object. The code utilizes a model that assumes a single
9 C* mismatch with no perturber and a double mismatch when the per-
10 C* turber is present. Given the complex reflection coefficients
11 C* with no perturber and with the perturber at two different posit-
12 C* ions, the phase constant, the relative phase velocities, and
13 C* the normalized frequency and phase velocity are calculated.
14 C*
15 C*****
16 C*
17 C* Input Variables:
18 C*   freq      frequency at which the group of data points was
19 C*             taken
20 C*   mga1,aga1 magnitude and phase of the reflection with no per-
21 C*             turbing object
22 C*   mga2,aga2 magnitude and phase of the reflection with per-
23 C*             turber at first position
24 C*   mga3,aga3 magnitude and phase of the reflection with per-
25 C*             turber at second position
26 C*   delz      distance between perturber positions
27 C*   offset    allows user to add an integer number of pi to
28 C*             phi
29 C*   n         number of data points in group. In first line of
30 C*             data group for a given frequency, it corresponds
31 C*             to the number of computed angles minus one. Can
32 C*             also be used on a line of its own to restart for
33 C*             non-consecutive data, in which case n more values
34 C*             are computed. n set to zero ends computation for
35 C*             that frequency group.
36 C*
37 C* Output Variables:
38 C*   phi,phia  phase difference and average phase difference be-
39 C*             tween perturber positions
40 C*   vrel,vrela relative phase velocity and average relative
41 C*             phase velocity
42 C*   beta,betaa phase constant and average phase constant
43 C*   kacotpsi  normalized frequency
44 C*   vccotpsi  normalized average relative phase velocity
45 C*
46 C*****
47 C*****
48     REAL FREQ,MGA1,MGA2,MGA3,AGA1,AGA2,AGA3,ANG,PHI,P1,DELZ,VREL,
49     [   BETA,PHIA,BETAA,VRELA,A,COTPS1,KACOTPS1,VCCOTPS1,RE,IM
50     REAL F,STEP,PC1,PC2,PC3,PC4,PHI1,PHI2,VREL1,VREL2,PHIMAX,PHIMIN,
51     [   VRELMAX,VRELMIN
52     INTEGER N,OFFSET,NAV,NDF,I,NCHAR
53     CHARACTER*60 CASE,HEADER
54     CHARACTER*10 OFILE,IFILE,PFILE
55     CHARACTER MODEL,FLAG,FDATA,DFILE*2,FORM*3

```

```

56      COMPLEX GA1,GA2,GA3,ARG,DATUM(20,51)
57 C
58 C
59 C
60      PI = 4.0*ATAN(1.0)
61      ANG = 2*PI/360.0
62      WRITE(1,*) 'CONSTRUCT DATA FILE? _'
63      READ(1, '(A1)') FDATA
64      IF(FDATA.EQ.'Y') THEN
65          WRITE(1,*) 'NUMBER OF DATA FILES TO BE PROCESSED? _'
66          READ(1,*) NDF
67          WRITE(1,*) 'NUMBER OF CHARACTERS IN DATA FILE NAMES: _'
68          READ(1,*) NCHAR
69          DO 110 I = 1,NDF
70              IF(NCHAR.EQ.1) DFILE = CHAR(I+64)
71              IF(NCHAR.EQ.2) DFILE = CHAR(I+64)//CHAR(I+64)
72              OPEN(8,FILE=DFILE)
73              READ(8, '(A1)') FLAG
74              READ(8, '(A60)') HEADER
75              READ(8,*) FSTART,FSTOP,NPOINTS
76              IF(NPOINTS.NE.51) GOTO 300
77              DO 105 J = 1,NPOINTS
78                  READ(8,*) RE
79                  READ(8,*) IM
80 105          DATUM(I,J) = CMPLX(RE,IM)
81 110          CLOSE(8)
82          WRITE(1,*) 'INPUT FILENAME: _'
83          READ(1,2) IFILE
84          OPEN(8,FILE=IFILE)
85          WRITE(1,*) 'TITLE LINE FOR DATA FILE(60 CHAR. MAX.):'
86          READ(1, '(A60)') CASE
87          WRITE(8, '(A60)') CASE
88          WRITE(1,*) 'ENTER HELIX RADIUS AND COT(Psi): _'
89          READ(1,*) A,COTPSI
90          WRITE(8,*) A,COTPSI
91          WRITE(1,*) 'ENTER DELZ: _'
92          READ(1,*) DELZ
93          OFFSET = 0
94          F = FSTART/1.E9
95          STEP = 5
96          DO 120 J = 1,NPOINTS,STEP
97              WRITE(8,*) F,NDF-1,DELZ
98              DO 115 I = 1,NDF
99 115          WRITE(8,116) REAL(DATUM(I,J)),AIMAG(DATUM(I,J))
100              ,OFFSET
101              F = F + STEP*((FSTOP-FSTART)/FLOAT(NPOINTS-1))
102              /1E9
103 120          WRITE(8,*) '0'
104          WRITE(8,*) '0 0 0 0'
105          FORM = 'CAR'
106          REWIND(8)
107      ELSE
108          WRITE(1,*) 'INPUT FILENAME: _'
109          READ(1,2) IFILE
110          OPEN(8,FILE=IFILE)

```

```

111         WRITE(1,*) 'INPUT FILE IN (POL)AR OF (CAR)TESIAN? _'
112         READ(1, '(A3)') FORM
113         END IF
114         WRITE(1,*) 'OUTPUT FILENAME: _'
115         READ(1,2) OFILE
116         WRITE(1,*) 'PLOT FILENAME: _'
117         READ(1,2) PFILE
118         OPEN(7,FILE=OFILE)
119         IF(PFILE.NE.'0') OPEN(9,FILE=PFILE)
120 C
121 C
122         WRITE(1,*) '(E)XACT OR (S)IMPLIFIED MODEL? _'
123         READ(1, '(a1)') MODEL
124         READ(8,3) CASE
125         WRITE(7,4) CASE
126         IF (MODEL.EQ.'E') WRITE(7,5)
127         IF (MODEL.NE.'E') WRITE(7,6)
128         READ(8,*) A,COTPSI
129         READ(8,*) FREQ,N,DELZ
130 10      WRITE(7,15) FREQ
131         NAV = 0
132         PHIA = 0.
133         BETAA = 0.
134         VRELA = 0.
135         PHI1 = 0.
136         PHI2 = 10000.
137         VREL1 = 0.
138         VREL2 = 1.
139         READ(8,*) MGA1,AGA1,OFFSET
140         IF(FORM.EQ.'POL') GA1 = CMPLX(MGA1*COS(AGA1*ANG),
141         [      MGA1*SIN(AGA1*ANG))
142         IF(FORM.EQ.'CAR') GA1 = CMPLX(MGA1,AGA1)
143 11      READ(8,*) MGA2,AGA2,OFFSET
144         IF(FORM.EQ.'POL') GA2 = CMPLX(MGA2*COS(AGA2*ANG),
145         [      MGA2*SIN(AGA2*ANG))
146         IF(FORM.EQ.'CAR') GA2 = CMPLX(MGA2,AGA2)
147         NAV = NAV + N - 1
148         DO 20 I=1,N-1
149             READ(8,*) MGA3,AGA3,OFFSET
150             IF(FORM.EQ.'POL') GA3 = CMPLX(MGA3*COS(AGA3*ANG),
151         [      MGA3*SIN(AGA3*ANG))
152             IF(FORM.EQ.'CAR') GA3 = CMPLX(MGA3,AGA3)
153             ARG = (GA3-GA1)/(GA2-GA1)
154             IF(MODEL.EQ.'E') ARG = ARG*(1.0-GA1*GA2)/(1.0-GA3*GA1)
155             PHI = ATAN2(AIMAG(ARG),REAL(ARG))/ANG
156             IF(PHI.LT.0) THEN
157                 PHI = -PHI/2.0
158             ELSE
159                 PHI = -PHI/2.0 + 180
160             ENDIF
161             PHI = PHI + 180.0 * OFFSET
162             BETA = PHI/DELZ
163             VREL = 2E9*PI*FREQ/(BETA*2.99E10*ANG)
164             PHIMAX = MAX(PHI1,PHI)
165             PHIMIN = MIN(PHI2,PHI)

```

```

166      VRELMAX = MAX(VREL1,VREL)
167      VRELMIN = MIN(VREL2,VREL)
168      WRITE(7,25) PHI,BETA,VREL
169      PHIA = PHIA + PHI
170      BETAA = BETAA + BETA
171      VRELA = VRELA + VREL
172      PHI1 = PHIMAX
173      PHI2 = PHININ
174      VREL1 = VRELMAX
175      VREL2 = VRELMIN
176 20    GA2 = GA3
177      READ(8,*) N
178      IF(N.NE.0) GOTO 11
179      PHIA = PHIA/REAL(NAV)
180      BETAA = BETAA/REAL(NAV)
181      VRELA = VRELA/REAL(NAV)
182      WRITE(7,30) PHIA,BETAA,VRELA
183      KACOTPSI = 2.0*PI*FREQ*A*COTPSI/11.8
184      VCCOTPSI = VRELA*COTPSI
185      IF(PFILE.NE.'0') WRITE(9,31) FREQ,PHIA,BETAA,VRELA,KACOTPSI,
186      [ VCCOTPSI
187      WRITE(7,35) KACOTPSI,VCCOTPSI
188      PC1 = (PHI1-PHIA)*100/PHIA
189      PC2 = (PHI2-PHIA)*100/PHIA
190      PC3 = (VREL1-VRELA)*100/VRELA
191      PC4 = (VREL2-VRELA)*100/VRELA
192      WRITE(7,36) PC1,PHI1,PC2,PHI2
193      WRITE(7,37) PC4,VREL2,PC3,VREL1
194      READ(8,*) FREQ,N,DELZ
195      IF((FREQ.NE.0).AND.(N.NE.0)) GOTO 10
196      STOP
197 300    WRITE(1,*)'NPOINTS NOT EQUAL TO 51!!'
198 C
199 C
200 2      FORMAT(A10)
201 3      FORMAT(A60)
202 4      FORMAT(5X,'Two boundary model using simultaneous equations',/,
203      [ 7X,A60)
204 5      FORMAT(7X,'***** Exact model used *****')
205 6      FORMAT(7X,'***** Small signal model used *****')
206 15     FORMAT(///5X,'Freq = ',F5.2,' GHz',/,10X,'Phi(deg)',8X,
207      [ 'Beta(deg/cm)',10X,'v/c',/,10X,8(' '),8X,12(' '),10X,
208      [ 3(' '),/)
209 25     FORMAT(10X,F8.3,10X,F8.2,10X,F7.5)
210 30     FORMAT(/15X,'Phi ave. = ',F8.3,/,15X,'Beta ave. = ',F8.2,/,
211      [ 15X,'v/c ave. = ',F8.5)
212 31     FORMAT(5X,F6.3,2X,F8.3,2X,F8.2,2X,F8.5,2X,F7.4,2X,F7.4)
213 35     FORMAT(15X,'kacot(psi) = ',F7.4,/,15X,'(v/c)cot(psi) = ',F7.4)
214 36     FORMAT(15X,'Phi varies by ',f5.1,'X(',f6.2,') and ',f5.1,'X(',
215      [ f6.2,')')
216 37     FORMAT(15X,'Vrel varies by ',f5.1,'X(',f6.4,') and ',f5.1,'X(',
217      [ f6.4,')')
218 116    FORMAT(2(2X,E11.5),2X,11)
219      END

```

APPENDIX C

DESCRIPTION OF METHODS USED TO GET COMPARISON DATA

1. Resonance Method

This method of calculating the phase velocity of a circuit is accomplished by building a small length of resonant circuit into which power is loosely coupled. The transmission characteristics can then be examined on a scalar network analyzer. At each frequency for which there is an integral number of half wavelengths along the total length of the circuit, a peak will be seen in the transmission. The frequencies at which these peaks occur are recorded, and the phase velocity is determined by

$$v_p = 2 * L * f / N$$

where L is the length of the resonant circuit, f is the frequency, and N is the number of half wavelengths present at that frequency.

2. Bead Pull Method

For this method of phase velocity measurement, a metal bead is pulled through the circuit. The bead is calibrated so that it moves a known distance along the circuit. The reflection of the circuit will have a sinusoidal type variation due to the bead moving through field maximums and minimums. From these data, the wavelength of the circuit can be determined and the phase velocity obtained from

$$vp = f * wavelength$$

where f is the frequency at which the data were taken. This method can be used on either cold test fixtures or actual circuits, but whichever is used, it is important to have a good match in order to get accurate

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