CONTROL OF MANUFACTURING DISTORTIONS IN WT4 MILLIMETER WAVEGUIDE MEDIUM

by

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ABSTRACT

A novel computer controlled mechanical measurement system for evaluation and control of transmission impairments due to geometric factors in circular multimode waveguide is described. Theoretical bases of this work are reviewed and some characteristic results from the system used for manufacturing control are described.

I. INTRODUCTION OF PROBLEM

The Bell Telephone Laboratories and Western Electric Company have been developing a new long haul millimeter wave communication system. The system will utilize the TE_{01} "Circular Electric" spatial mode for information transmission. This mode has the theoretical property of monitonically decreasing attenuation with increasing frequency. The transmission media will consist of discrete circular sections 60 millimeters in diameter, and approximately 9 meters long. The system will have seven sub-channels distributed in the 40 to 110 GH range. Two level DCPSK modulation will produce a system with a capacity for 230,000 voice channels.

The electrical loss in the transmission media will be approximately one db/km. Each individual section will therefore have an average loss of less then 0.008 dB, which requires resolution beyond the reliable range of present test equipment. Also, any electrical measurements of the steel substrate prior to copper plating would characterize principly the surface resistivity of the steel tubing and not the finished waveguide medium. It is economically imperative that the quality of the media components be established as early as possible in the manufacturing process, not only to minimize processing of unacceptable waveguide sections, but also to improve the local yield by signaling the operator whenever the process reaches an undesirable limit.

There are no practical direct electrical performance tests that can be implemented on bare steel tubing. However, detailed electrical transmission quality of individual waveguide sections can be established from the knowledge of the geometric imperfections in the guide. This paper will review the principal theoretical basis for the approach and also discuss a system that is presently being used to screen waveguide sections at a tubing mill.

II. BACKGROUND

The general theory relating geometric distortions to electrical performance was established by Schelkunoff[1]; who demonstrated the transition from Maxwell's equations to the generalized telegraphers equations. Morgan's specialization of these results to circular waveguide resulted in a formula for coupling coefficients between different normal modes for specified geometric distortions[2]. Since that time, various workers (Unger[3], Carlin and D'Agostino[4]) extended these results to different guide structures and to broader classes of normal modes. Parelleling this work were developments by Warters and Rowe describing the effects of multiple and continuous imperfections in statistical terms[5]. As they bear on the present problem, these developments can be summarized by describing the radius of the waveguide in terms of a Fourier series

$$r(z,\theta)=r_n+1/2\ a_o(z)+\sum_n a_n(z)\cos n\theta+b_n(z)\sin n\theta \qquad (1)$$

in which r_N is the nominal radius, z the axial distance along the guide, and θ the angle around the guide from some reference plane. The a's and b's are the fourier coefficients as functions of axial position, with the index n usually referred to as the foil. It is known that the presence of a n-foil distortion gives rise to coupling between modes differing by an angular index of n, that is

$$TX_{i,p} \xleftrightarrow[a_n,b_n]{} TX_{i\pm n,q} \qquad (2)$$

Qualitatively the coupling between two modes is given by the product of a normalized coupling coefficient and the appropriate fourier coefficient describing the distortion, and while the normalized coefficients are all of about the same magnitude it has been found in practice that the foil n=1 distortions (axial offset or curvature) are much larger then other geometric distortions.

$$TE_{01} \xleftrightarrow[\text{curvature}]{} TX_{1,n} \qquad (3)$$

The effects of the different modes, to second order, are independent and the mode conversion loss may be approximated by

$$\alpha_{MC}=1/2\sum_{\text{modes}}\Xi^2_{1,n}\left[S_{a_1}(\Delta\beta_n)+S_{b_1}(\Delta\beta_n)\right] \qquad (4)$$

where Ξ is Morgan's coupling coefficient and Δb the imaginary part of the differential propogation constant*, and S_{a1}, S_{b1} represents the power spectral density of the function $a_1(z)$, $b_1(z)$ respectively and $\Delta\alpha$ is small.

III. DATA AQUISITION AND SIGNAL PROCESSING

For simplicity in processing, the deviation from a perfect right circular cylinder is decomposed into two principal effects: the first component deals with the deviation of the cylinder from straightness (curvature); the second component deals with the deviations of the cross-section from circularity. Two separate gauges have been developed to rapidly track the two types of distortions.

Curvature Gauge

The curvature gauge is fundamentally composed of two independent three-point structures , it is shown in Figure 1. There are two fixed points and one movable, the latter is connected to a linear differential transformer. Since three points in a plane define a circle, it is, therefore, possible to interpret the transformer output reading as a change in the radius of the circle. In practice, it is more useful to directly compute the curvature, which is the reciprocal of the radius of curvature in the plane.

Curvature Processing

The curvature data, $c(n\ \Delta z)$, is obtained for each centimeter of displacement, Δz, until 1024 points are collected, or an end of data condition is reached. The resultant sequence is then unbiased, pre-whitened, and a 10% cosine window is superimposed on the data to minimize the end effects when the spectrum is generated.

Spectrum

The spectrum is computed using an adaptive prewhitening technique. Supposing that N samples of the curvature function $c(z)$ spaced Δz meters apart are aquired, the autocorrelations r_k are computed for $k=0,1,2,..K$ by the formula

$$r_k = \frac{1}{N-k} \sum_{n=1}^{N-k} (c(n)-\bar{c})(c(n+k)-\bar{c}) \qquad (5)$$

where $\bar{c}$ is the average of the $c(n)$'s. From these we form an estimate of the Wiener one step predictor, α, defined by the Yule-Walker equations:

$$r_k = \sum_{j=1} \alpha_j\, r_{|j-k|}\ ;\ k=j,\ \ldots K;\ \alpha_0=-1 \qquad (6)$$

These coefficients are used to define a whitened data sequence, y, by means of a prediction error filter

$$y_n = [c(n)-\bar{c}] - \sum_{j=1}^{k} [c(n+j)-\bar{c}]\,\alpha_j \qquad (7)$$

and $n=1, 2,..N-k$. The purpose of this operation is to reduce the requirements on the filters in subsequent operations as the y sequence is much closer to white than the original data. The spectrum may now be computed using a M point FFT algorithm and is given by

$$S(j\Delta_f) = \frac{G(j\Delta_f)\Delta z}{N-K} \cdot \frac{\left|\sum_{n=0}^{N-K-1} Y(n+1)w(n+1)e^{\frac{i2\pi nj}{M}}\right|^2}{\left|\sum_{n=0}^{k}\alpha_n\, e^{i\,\frac{2\pi nj}{M}}\right|^2} \qquad (8)$$

where $G(\Delta f)$ is gauge correction factor, $\Delta f = 1/(M\ \Delta z)$, and the data window, W, is the Tukey spliced cosine. The data window is used to eliminate the very slowly decaying side lobes associated with simple truncation of the data. The above expression for the spectrum has two distinct parts: the numerator, which represents the spectrum of the residuals and the denominator which represents the correction for the prediction error filter transfer function.

This row spectrum estimate is then smoothened by means of a five-point filter and the appropriate results are displayed on the plotter as shown in Figure 2. After the display of the Curvature PSD for a given tube, the computer generates a reference specification curve, which by comparision then indicates the relative quality of the tube as a function of the spatial frequency. The spectral signature can be converted to a conventional " radius of curvature" for a given special frequency, f, as follows:

$$R_c(f) = 2/\sqrt{S(f.)\Delta_f} \qquad (9)$$

Cross-Section Gauge

The cross-sectional gauge is to a two-point diameter gauge, it is shown in Figure 3. The even ordered foiling distortions are detected by rotating the tube with respect to the gauge. In practice, this rotation is accomplished as the gauge is traveling in the tube; thus a forward and reverse helical path is scanned for the cross-sectional geometry of the tube.

Foil Computation

The diameter gauge is strobed 64 times per tube revolution. The diameter measurements are converted into radial deviation readings from a reference circle. This deviation information is then transformed by the FFT algorithm into angular periodicity terms (foils). The result being:

a_i, b_i for i=0,2,4 ..32

(odd foil surpressed by gauge symmetry)

For loss analysis purposes, it is desirable to convert this foil componetnt information into average effective amplitude. This is accomplished by computing the respective F , where:

$$F_i = \sqrt{a_i^2 + b_i^2} \tag{10}$$

and then averaging all of the respective F terms for the tube. The average foil amplitudes are then plotted on an X-Y plotter as shown in Figure 4.

IV. SYSTEM HARDWARE AND CONTROL

Hardware Configuration

The principle system hardware configuration is depicted in Figure 5. The signal conditioning provides the necessary carrier excitation, synchronous demodulation and amplification for the linear differential transformers employed in the diameter and curvature gauges. The transducers operate at a carrier frequency of 2.5 KH . The two digital voltmeters (DVM) perform time averaging and the analog to digital conversion for the system. The DVM's are triggered independently by the mechanical drive system. The minicomputer used in this application is a Hewlett-Packard 2116C computer with 16K of 16 bit core memory. The output of the computer processing is a series of graphs produced on an X-Y plotter.

Operational Control

The modes of operation of the measurement test set are selected by means of sense switches which are present in the computer. There are over ten measurement strategies available from which the operator can choose; these range from rapid minimum output production test to extensive diagnostic output.

Operational History

This system has performed well over the span of the current development cycle. It has reliably screened over 3000 waveguide sections under hostile environmental conditions. The system is in operation at a tubing mill where there exists a high electrical noise level and many corosive factors. The present system has a throughput of at least four tubes per hour; much of this time is consumed in tube handling and calibration procedures.

V. SUMMARY

The electrical performance of millimeter waveguide media can be predicted from the statistical knowlwdge of the geometry of the transmission media. A system for monitoring and controlling the quality of the millimeter waveguide process has been described. This system typically displays the information in Spectral form. This interim data form is particularly usefull because it can be easily converted to a conventional geometric form by means of Equation 9 or to an electrical loss estimate by means of Equation 4.

VI. ACKNOWLEDGEMENT

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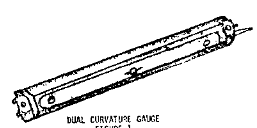
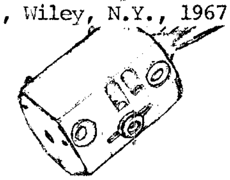
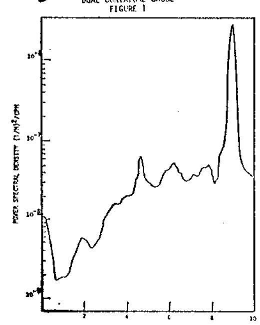


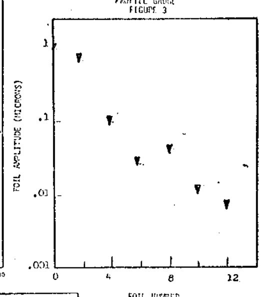
DUAL CURVATURE GAUGE
FIGURE 1



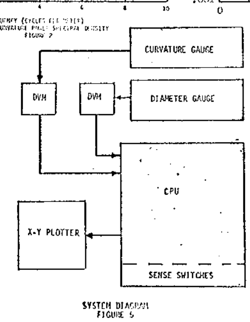
PROFILE GAUGE
FIGURE 3



SAMPLE CURVATURE POWER SPECTRAL DENSITY
FIGURE 2



EFFECTIVE FOIL DISTORTION
FIGURE 4



SYSTEM DIAGRAM
FIGURE 5