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SURVEY OF NON-DESTRUCTIVE TIRE INSPECTION TECHNIQUES

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16. Abstract

The status of several promising methods for non-destructive tire inspection is surveyed with the conclusion that radiographic, infrared, holographic and ultrasonic techniques warrant further evaluation. A program plan is outlined to correlate non-destructive tire inspection data to tire failure data. The emphasis is on inspection systems having sufficient resolution and discrimination capability to detect a broad range of "anomalies." The inspected tires will be subjected to dynamic wheel testing such as specified in Safety Standards 109. Failed tires will be analyzed to determine those anomalies that lead to tire failure and eventually to provide a capability for failure prediction based upon non-destructive inspection techniques.

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INTRODUCTION

The purpose of the Nondestructive Tire Testing Program at TSC is to apply NDT technology to the detection of faults in tires that could lead to their abrupt failure, or at least to an inability to perform their function safely. The initial effort is being concentrated on quantitative characterization of tire anomalies as seen by several NDT methods, and investigation of the relationships between such anomalies and tire behavior.

The development of reliable detection methods will have a significant impact on compliance testing of new tires, inspection of tires in service, and inspection of remanufactured tires (retreads). While NDT inspection is of great importance in each of these areas, the increasing costs and limited availability of facilities for compliance testing lend primary importance to application of NDT to prior screening of compliance test samples. The goal in this case is to develop suitable methods to single out those tires that are most likely to fail the compliance test. Since only 1-2 percent of the tested tires fail, an NDT method that could reliably predict which tires will fail could increase the sample size by a factor of 50 without appreciably increasing the cost of compliance testing, or conversely, could reduce the number of tires to be so tested. Either path presents sufficient reason for the performance of this work.

Early in this program, it became apparent that the relationships between specific tire defects and tire failures have not been fully established. Clearly some irregularities of construction, which could be identified as "manufacturing defects", are benign, and do not result in tire failure. The general program philosophy then resolved to define various types of tire defects together with measures of their severity, to follow their progression to failure, and simultaneously to develop NDT methods which will reliably and economically detect and characterize defects. The first part of this problem, to define the types and measures of the severity of tire defects, represents the area where emphasis must be placed first. The schedule for FY72 is directed, in the main, to its solution.

The approach being used in this program is 1) to use currently available NDT methods to inspect tires at various stages of use, 2) to exercise the tires using either compliance or road test procedures, 3) to perform failure analysis on tire sections at different stages, and 4) to correlate the non-destructive inspection results, failure statistics, and failure analysis data.

It is an accepted fact that the cord-adhesive-rubber-wire composite comprising a tire is a very complex structure. The complex dynamic interaction of each of the parts is further complicated by wide variations in materials of construction, the ever-increasing number of structural configurations, and use in a wide variety of vehicles with individual characteristics.

The Materials section surveys briefly some of the available background information on tire materials and structure indicating the necessity for understanding the interaction of the tire components and the nature and mode of propagation of defects. The section also explains techniques for laboratory fabrication of test specimens, and describes instrumentation available for characterization of stock materials and composites.

The third section discusses the general plan for studying the correlation of nondestructive inspection data with tire failure statistics and failure analysis data. Four primary NDT techniques are considered sufficiently promising and sufficiently well developed for such evaluation. The four techniques, Radiography, Infrared, Optical Holography, and Ultrasonics, are separately reviewed as to history, present status of development, and plans for implementation for evaluation purposes.

The section entitled Secondary NDT Methods describes some of the additional techniques which will be investigated as interest, time, and funding allow. These techniques either measure tire parameters that are not measured by the primary methods, or they represent a less costly or more specific method of accomplishing a similar measurement.

The final section contains the conclusions and specific recommendations resulting from the work already done on this program.

MATERIALS

A materials area was included in this program for the following purposes:

- To relate the chemical, physical, and mechanical properties of the materials of construction to the failure modes and defects that occur in tires.
- To fabricate specimens of tire fabric and rubber composites with simulated defects to be used for calibration of the several nondestructive testing methods.
- To conduct various tests such as temperature of cure, degree of cure, tensile strength, and other physical and chemical properties of the particular composites used in the work on this program.

BACKGROUND

An understanding of the chemical and physical properties of the tire composite is necessary in order to evaluate fully the failure modes and mechanisms that occur. A tire is composed of several different types of rubber (elastomers) both natural and synthetic. The cord may consist of rayon, nylon, polyester, glass, or steel, and the tire may have combinations of two of these. In addition, the following materials are present in significant quantities: carbon blacks, accelerators, plasticizers, cure activators, sulfur and sulfur compounds, antiozonants and waxes. The amount of each type of rubber, cord, and additive varies with the manufacturer and with tire grade and size, and is held highly proprietary.

The types of rubber used include natural rubber, polyisoprene, styrenebutadiene, polybutadiene, butyl, chlorobutyl, neoprene, and EPDM. There are special compound requirements for the different areas and components in the tire. For example, the tread must have special wear and traction characteristics and must be cool-running for durability. These requirements are best met with the use of two different compounds selectively distributed in the tread, an arrangement known as cap/base construction. The cap compound furnishes the desirable wear and traction properties, while the base compound is highly resilient and cool-running. Cap/base construction is used as a method of reducing the temperature in the shoulder region, normally the hottest region of the tire. High operating temperatures cause degradation of both the elastomers and cord materials.

A special resin called formaldehyde resorcinol latex (henceforth "FRL") is used as an adhesive to improve the bond of the cord to the rubber. This resin does not adhere to fiberglass cords, and a new adhesive had to be developed for that fiber based on a silane adhesion promoter.

Aside from bruises, it is widely held that tire failures begin at this cord/adhesive/rubber interface. The Fabric Research Laboratories, Dedham, Mass., has been studying this problem for several years under contract to the Office of Vehicles Research, National Bureau of Standards[1]. Tire failure may be caused by the propagation of a small disbond into a large delamination, or may be caused by breakdown of the cord reinforcement, weakened by the combined action of high temperatures, cyclically imposed deformations, and intermittent shock loadings encountered in use. Under these conditions, one or more of the components in the system of cord-adhesive-rubber undergoes sufficient degradation to initiate abrupt failure of the tire. In an abrupt failure, degradation appears to take place rapidly without any prior indication of mechanical weakening of the system components. Even though the changes at the cord level are not externally detectable, they nevertheless are measurable, and the ultimate failure of the tire cord, while appearing to be sudden in nature, is in effect the culmination of a gradual degradation process. It appears that once degradation is initiated in a tire system, total failure is inevitable, but can be retarded. Cord degradation, per se, is a gradual phenomenon, but individual filaments within each cord fail catastrophically. Attention should then be focused on how degradation is initiated, and some means developed to detect the incipient failure at this stage.

When the cord and its surrounding matrix of rubber and adhesive are placed in axial tension or compression, the natural radial and circumferential deformations of these components differ, which creates problems when the bonded three-phase system is deformed either statically or dynamically. Both experimental studies and theory reveal that the compressed cord will tend to increase in diameter more than the surrounding rubber matrix. Further, the adhesive tends to bond individual filaments within each yarn ply in the cord, causing each yarn to behave as a monofilament and the cord to behave either as two or three monofilaments, concentrating circumferential cord growth during cord compression at the ply lines. Consequently, dynamic strain cycling of cord-adhesive-rubber three-phase systems induces extremely high local strains circumferentially in the adhesive at each ply line.

In addition, the strain deformation of the cord tends to follow very closely the stress applied to the three-phase system, while the elastomer tends to be hysteretic, that is, its strain deformation lags behind the applied stress. Consequently, during compression and tension cycling, very high normal forces can be induced across the adhesive interface between cord and elastomer. The effect of these stresses acting across and locally within the adhesive film interface can lead to the ultimate degradation of the cord-reinforced system.

Given the variations in materials and manufacturing processes, one could expect that degradation would proceed at different rates in different tires. It is possible, also, that the response to ultrasonic and other detectors will vary.

A literature search was initiated, and is continuing, to develop a background and to keep current in the chemistry and application of the materials of construction of automobile tires. For example, the temperature at which degradation becomes significant, and the effect of dwell times at various elevated temperatures is highly significant. The mode and rate of degradation of each type of material are obviously different, and their interaction during degradation is an integral step in the failure of the total system.

Visits were made to a number of tire manufacturers, including Uniroyal, Goodyear, Goodrich, and Armstrong. Tire manufacturing processes were observed in detail, and discussions were held with company personnel to try to determine the principal defects in tires and the efforts that are being made to detect them. Questioning as to the causes of these defects was less successful. The materials laboratories were visited to see the materials testing equipment. Samples of ply materials were obtained, enabling us to fabricate our own specimens. We were informed, however, that the exact composition of the uncured rubber is proprietary and that what we received is not an actual sample from current production, but is representative of compounds typically used.

A visit was made to the Tire Systems Section of the National Bureau of Standards and to Dr. Cecil Brenner, Section Chief. At this installation, work has been in progress for several years on most aspects of tire dynamics, and more recently on non-destructive testing. No materials work, per se, is being done in this section.

Professor Sam Clark (U. of Michigan Tire Program), the Highway Safety Research Institute (Ann Arbor, Michigan), and the Smithers Laboratory (Akron, Ohio), were also visited. Professor Clark has been a consultant to the tire industry for many years in the area of tire dynamics, and has submitted a proposal to TSC for additional work. The Highway Safety Research Institute work also involves tire dynamics as well as studies of traction and wear. They are also collecting statistics on accident rates and causes. The Smithers Laboratory performs numerous tests on tires from all American and some foreign companies, and publishes this data periodically.

Contact was also made with the Fabric Research Laboratory which has been under contract to the National Bureau of Standards for research on fatigue of the cord-adhesive-rubber interface. This work has involved molding single cords of the three major types into small rubber blocks, which are subsequently exercised in the Goodrich disc compression tester. A great deal of information on the mechanism of degradation has resulted from this work, and much of it will be quite valuable to our program.

Since it is anticipated that NDT inspection will eventually be used for validating the selection of old carcasses for retreading, the plants of two retreaders were visited. The procedures for selection, grinding and retreading were observed closely as a preliminary for later recommendations for improvement by means of NDT.

LABORATORY FABRICATION OF TEST SPECIMENS

A program was set up in our laboratory to fabricate specimens of tire ply and covering rubber which would contain specific built-in defects. The object was to provide simulated tire defects to the instrumentation group in this program for purposes of calibration of the ultrasonic and holographic techniques. Materials used were a nylon cord ply material 0.035 inch thick (Uniroyal Stock No. U-100A), and carcass rubber coating stock 0.031 inches thick (U-100). A press with heated 4 x 4 platens was used to cure the specimens, typically at 360°F. for 20 minutes. Radiographs were made of each piece, as well as thickness and durometer measurements.

Twenty-four specimens were made including the following configurations:

a. Two plies of U-100A (see above)
b. Four plies of U-100A
c. Two plies of U-100A plus two of U-100 as top and bottom covers
d. Four plies of U-100A plus two of U-100
e. A one-inch diameter disbond in types a. and c.
f. A one-inch diameter disbond between cord plies 1 and 2 in type d.

g. A one-inch cord cut in one ply of type c.

h. A one-inch cord cut in both plies of type c.

i. One-half inch and one-inch cord ply overlaps in type c.

j. An extra half-ply of cover rubber added to type c. to produce irregular rubber thickness.

Type b. composites had a typical thickness of 0.120 inch, and type d. was 0.160 inch thick. Shore A hardness was 60-70. The disbonds were created by precuring the one-inch diameter areas and did not involve the use of plastic films which could create spurious signals.

A new press has been received which has nine-inch heated platens. The 8 in. x 8 in. specimens which we have begun to fabricate are much more satisfactory, in that the defects deliberately introduced can be isolated from end effects.

Work has also begun on the fabrication of tubular specimens for laboratory testing. According to the recommendations of Prof. S. Clark, the tubes will be 13 inches long and will have an outside diameter of two inches. They will consist of two plies of cord material separated as well as covered by all-rubber skim stock. After wrapping on a mandrel, the composite will be inserted into a cylindrical mold, a bladder on the inside will be inflated to 100 to 200 psi, and the entire assembly will then be heated in an oven for curing at about 160°C. To allow investigating both the rubber and cord characteristics in a relatively independent manner, two different ply orientations are being fabricated. In the first, a bias ply with equal cord angles (55° from the long axis) will be stressed in an oscillatory torsional manner about the long axis to allow investigating rubber characteristics. In the second, the plies will be laid normal to and parallel to the long axis and will be stressed in a translational oscillatory manner along the long axis to allow investigation of cord characteristics. The first ply orientation does not appear to present any fabrication problems. The second configuration will be fabricated using a spiral wrap of a narrow strip of ply material for the direction normal to the long axis.

SPECIAL INSTRUMENTATION FOR MATERIALS STUDIES

A Differential Scanning Calorimeter has been used to determine the cure temperature of the uncured ply material. This instrument has the capability to measure the exotherm of a curing reaction on a 20 mg. sample. It can be used to determine the temperature range of the curing process and the heat of reaction and can thus detect whether a sample of rubber has been fully cured. This will also be useful when specimens are prepared with weak bonds between plies.

A thermogravimetric analyzer will soon be put into use to measure the weight-loss of the rubber composite over the temperature range of interest. This will also give some indication of the extent to which off-gasing at high operating temperatures can influence the size of a delamination.

A Reichert MeF2 metallograph is being used for microscopic examination of failed areas to determine the precise mechanism by which cords and rubber separate, and the extent of propagation of the separation. A microtome will be obtained in order that specific areas of interest can be sectioned. The scanning electron microscope will also be used for higher magnification, 3-dimensional views of such areas.

PRIMARY NDT METHODS

This section describes the four primary NDT methods that are being implemented initially for actual tire inspection. It is anticipated that these methods will provide a detailed visualization of the major tire components and important tire material interfaces. Prior to actual tire inspection, each NDT method will be calibrated on known defects to determine its characteristic response to representative defects of varying severity. This "signature" data will form the basis for subsequent analysis of tire data, to permit operator interpretation and logging of inspection results. To allow correlation of results among the several NDT methods, techniques are being devised for determining and comparing the locations of tire anomalies detected by the various methods.

The operator-interpreted data from each NDT method, the positional information, and tire identification will be fed into a computer-readable data base, and analyzed to determine the correlations among various parameters. For instance, it will be possible to investigate the frequency of occurrence of various faults, the positional correlation between failures and defects, the propagation of defects with service, and other relationships as required.

RADIOGRAPHY

BACKGROUND

X-ray techniques have been used for several years to inspect tires. Until recently, their use required recording the images on film. Film processing, because it is both expensive and time-consuming, has prohibited the general application of X-ray tire inspection. Attempts to overcome this limitation resulted in the adoption of medical fluoroscopy equipment. The early attempts using fluoroscope screens and direct viewing were generally unacceptable due to poor image contrast. In the early 1960's, a few pioneering systems using image intensification techniques were made. These systems were also found lacking in contrast. This problem occurs because the tire components to be imaged do not exhibit significantly different absorption of X-ray photons than the surrounding rubber. To enhance the differential absorption, operating energy from 15 to 50 KV is necessary. Unfortunately, the conventional 6 inch and 9 inch image intensifiers are made by incorporating the fluorescent screen inside the glass envelope. The amount of glass necessary to maintain structural integrity of the X-ray image intensifier is so thick that most of the photons in the primary range of interest (15 to 30KV) are absorbed.

Considerable work was done in the mid 1960's on the substitution of beryllium for the glass window on the tubes, but the technical problem of making a vacuum tight seal on windows of the size necessary proved insurmountable. Concurrently, the Old Delft Company in Holland was active in building chest photo-fluorographic equipment for mass chest X-ray surveys. As a consequence of this work, they developed an expertise and the necessary optical system to gather light from a 14 inch x 14 inch screen with good efficiency for photographic uses. In the mid 1960's, their optical system was combined with a high quality CCTV (closed-circuit TV) system. The resulting fluoroscopy system was called the "Delcalix." system. Early models used an image orthicon. In 1969, an improved model was introduced employing an isocon camera tube. Compared to the conventional glass-faced X-ray image intensifier - CCTV combination, the modern Delcalix System offers an 18.7 times gain in brightness at 60 KV and a 711 times gain in brightness at 35KV. In addition, the input area is more than twice as large as that for the older method. The Delcalix unit was introduced to the tire market in 1970 and has been accepted as the industry standard. While film does provide higher spatial resolution and greater contrast, the ability to manipulate and view the tire in real time using the Delcalix type imaging system makes X-ray tire inspection a practical method.

The types of tire anomalies and defects that can be detected by the X-ray technique are those that relate to the structure of the absorbing tire components or to the presence of air bubbles. X-ray absorption is essentially proportional to the total mass of matter along the ray path. Since delaminations do not change this total mass along a ray path normal to the surface, they are not likely to be detected unless the view is such that ray paths run parallel to the delamination surfaces allowing a reasonable change in attenuation to occur. Even with this limitation, the ability to view in detail the tire components and their relative positions provides a good check on the manufacturer's quality control, and supplies definitive information on the internal structure of each tire for correlation with other NDT data.

X-ray tire inspection systems based on the Delcalix imaging system are manufactured by Westinghouse Electric Corporation and by General Associates, Inc. Units have either been purchased or are in use at Goodyear Tire and Rubber Co., B. F. Goodrich Company, Uniroyal Inc., and Firestone Tire and Rubber Company.

LABORATORY PROGRAM

Of the four primary NDT methods being investigated, the X-ray technology is the most advanced and does not require any developmental work. Our efforts in this area are designed to make the necessary tools available to allow efficient inspection of both laboratory samples and tires. Laboratory samples and tire segments are being evaluated with a Faxitron Model 804 laboratory X-ray unit made by the Field Emission Corporation. This unit will accept flat samples up to 12 inches x 12 inches in size. Accelerating voltages range from 0 to 110KV. This capability is adequate for the evaluation of the laboratory specimens.

An X-ray tire inspection system similar to those offered by General Associates Inc. and Westinghouse Electric Corporation is being procured as our primary NDT inspection method. Assuming reasonable delivery time, this equipment should be in-house and operating in September 1971. Equipment evaluation should take about one month. At the conclusion of this equipment evaluation, tire inspection will begin.

An interim capability to X-ray tires is being provided by the U. S. Army Materials and Mechanics Research Center at Watertown, Mass. Standard industrial X-ray machine and film techniques are used. The necessity to cut and hold film against the tire makes this method quite inefficient and limits our use of this capability to inspecting a few selected tires.

INFRARED

BACKGROUND

Infrared testing of materials has a long and successful history. Based upon this history and the belief that most tire failure mechanisms exhibit a characteristic localized heat signature, infrared has been considered as one of the most promising nondestructive test methods. The desirability of remote monitoring of the infrared emission of tires has prompted most of the major users and suppliers of tires to investigate this method. Included in this group are the Firestone Tire and Rubber Company, Goodyear Tire and Rubber Company, General Tire and Rubber Company, Gates Rubber Company, National Bureau of Standards, and the Department of Defense. The reported results have not conclusively established the worth of the infrared method for detecting latent faults. However, it is generally believed that just prior to failure, a tire being exercised does exhibit a significant signature.

LABORATORY PROGRAM

The general art of infrared imagery and its attendant data collection and analysis is well advanced. However, the scanning systems designed for imaging scenes and stationary objects are not generally appropriate for a spinning tire, and the usual image display is severely limited for quantitative interpretation. On the other hand, infrared sensors with adequate sensitivity and speed of response are commercially available. One such sensor is manufactured by Sensor Inc., and uses room-temperature InSb coupled to a wide bandwidth amplifier. This sensor is being used in a scanning system being put together in-house. The rotation of the tire on a test wheel will provide the horizontal scan and the sensor will be sequentially stepped about the tire cross section to provide the vertical displacement. A typical system configuration is shown in Figure 1. The equipment will acquire temperature readings from 4000 resolvable elements of tire surface (including tread and sidewalls). The matrix describing the surface temperature variations will be sampled during the build-up of the tire temperature. The data can be stored digitally on magnetic tape and analyzed by computer for display of equal-temperature contours, temperature profiles along scan lines, etc., and the time variation of these and other topological features can be examined as the temperature builds up, to determine what aspects of the data correlate best with tire faults. It is hoped that false alarms due to normal non-uniformities of tire structure will be eliminated by this type of examination. We hope to automate the decision-making equipment on the basis of our correlation studies. However, the initial images or thermograms produced by this system will be interpreted by the operator.

A second part of the laboratory program is to obtain infrared information on tires undergoing wheel testing (such as during compliance testing). The recording and analysis of the complete time history of the build-up of the temperature distribution will require use of automated data reduction. The simplest method is to provide an alarm when the temperature reaches a preset level. While this may permit shutting down the test before the tire fails, it does not yield data concerning the rate of temperature

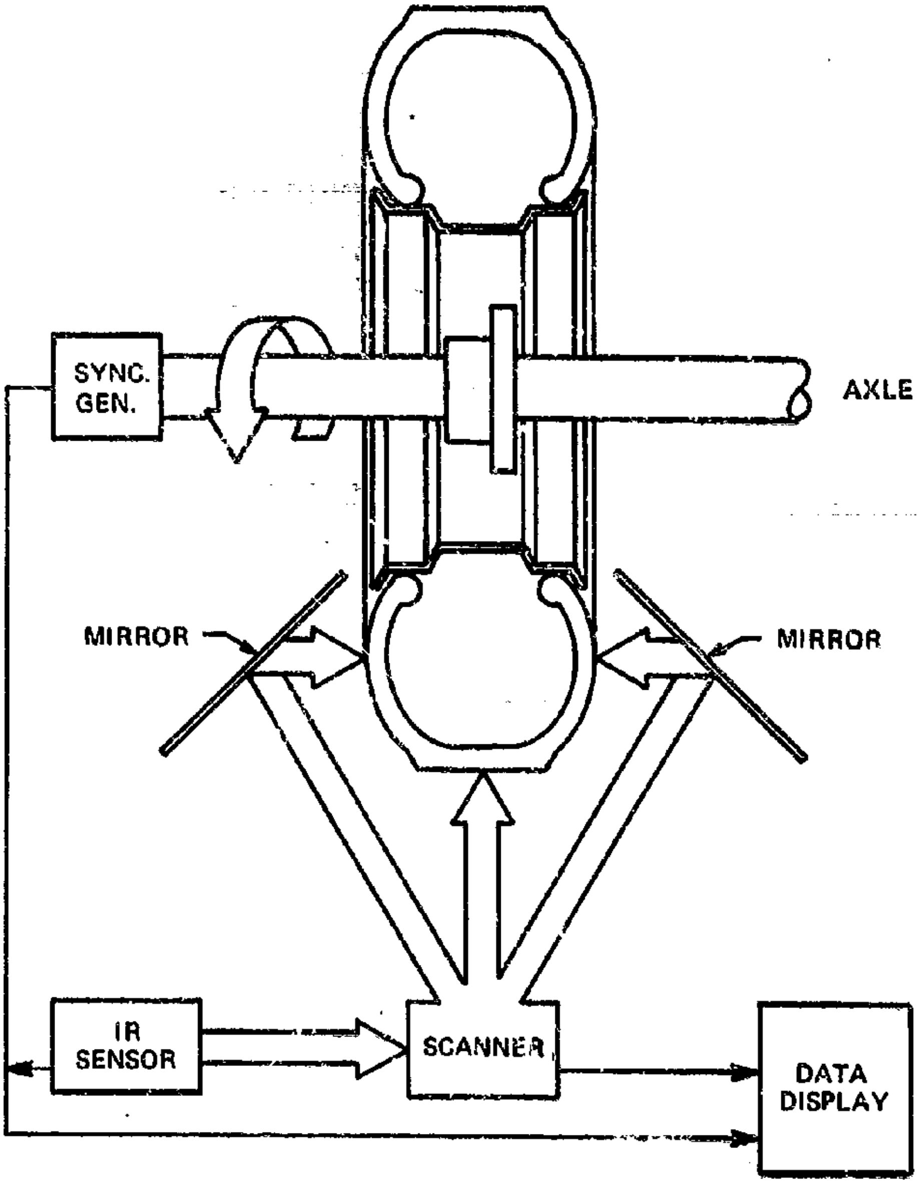


Figure 1. Infrared Test System

build-up and the extent of the build-up area. A periodic sampling of the thermal profile resulting from rotation of the tire would provide some data on the temperature build-up. Initially, only the more limited types of data will be obtained at a compliance test center and, as more advanced data handling methods become available, additional data can be obtained tracing the variations in the temperature distribution during the failure process.

Infrared inspection of tires appears to have many advantages in simplicity of technique and apparatus as well as in the potential for detecting the faults arising from a variety of mechanisms.

The basic technique is described in Figure 2. A tire mounted on a rim is caused to rotate by pressing a rotating roller against the tire as shown. The stresses applied to the tire are similar to those imposed in rolling over a road. The tire undergoes periodic flexing, and internal friction generates heat in the tire structure. A distribution of temperature develops, the precise spatial and temporal variation of which is, of course, dependent on the distribution of heat generation and on the variations in specific heat, mass density, and heat conductivity within the tire.

A perfect tire may be expected to have a temperature distribution corresponding generally to the variations in flexing in different regions of the tire. Except perhaps for minor modulation due to the tread pattern, the surface temperature would be independent of the circumferential coordinate θ corresponding to rotation of the wheel, and would depend only on position in the cross-section plane, which may be measured by the angle coordinate ϕ as indicated in Figure 3.

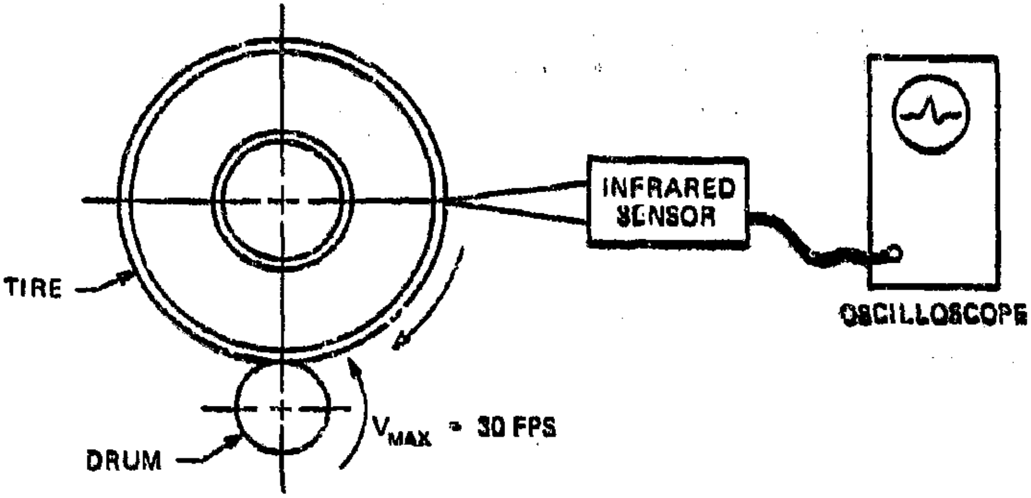


Figure 2. Tire Inspection Using Infrared Technique

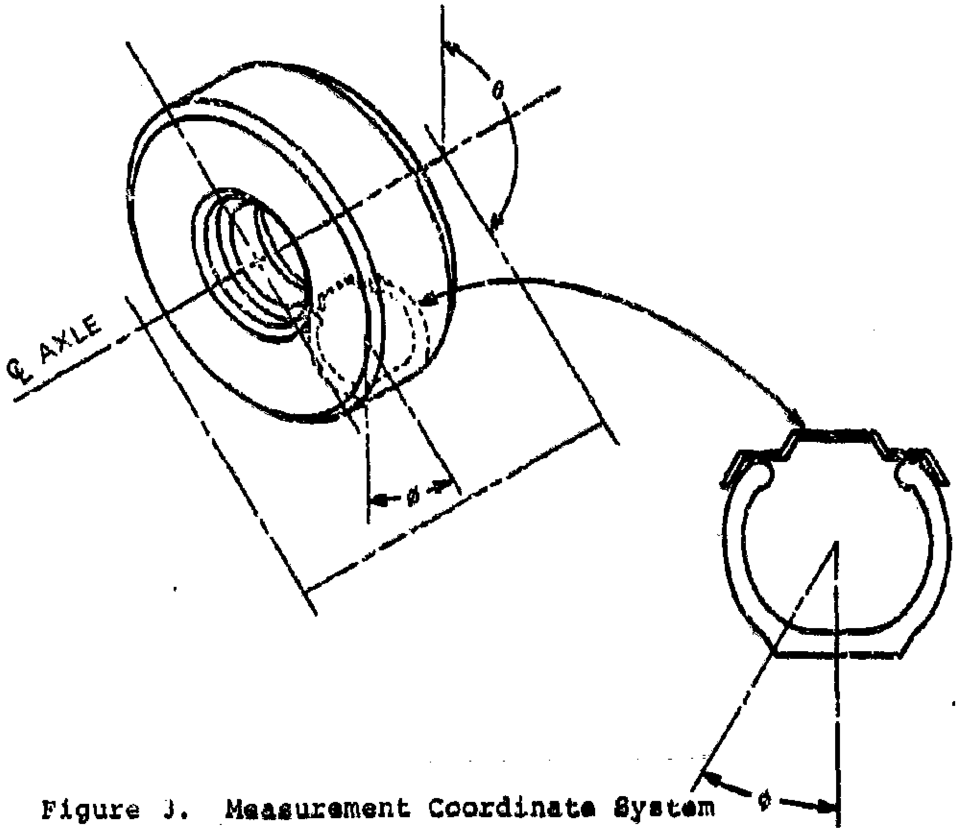


Figure 3. Measurement Coordinate System

The distribution of heat generation along the ϕ-coordinate is determined by the mass distribution and cord distribution. We may expect then, for a good tire, that the temperature profile in the plane defining ϕ will be stationary in shape as the temperature builds up. Variations from this stationary profile may be caused by tire imperfections. The problem of tire fault detection with infrared radiation is defined as follows:

1. What is the minimum detectable temperature variation?

2. What spatial temperature distributions do tire construction singularities produce?

3. What construction singularities are responsible for tire failure?

We see that there are really two separate problems. First, there is the problem of recognizing the temperature signatures of a variety of construction singularities. Secondly, and quite independent of the detection problem, is the problem of determining the relationship between tire construction singularities and the mechanics of tire failures.

The immediate problem is that of detection. The radiation emanating from the tire is a measure of its temperature. At room temperature, the peak of the spectral distribution as obtained from the Wien displacement law, $\lambda T =$ 0.288 cm. deg., is about 10 microns. We must, therefore, be prepared to detect radiation of that wavelength. Intensity variations will be adequate to estimate the magnitude of small temperature variations. Experimental evidence also assures us that temperature variations may be expected to be under 50° K. While it is customary, in measuring temperatures by radiation emission, to compare the object to be measured with an object of known temperature by a periodic chopping process, there is no need for chopping in a system which is regularly scanned and where only variations from a uniform temperature are to be considered.

Two considerations are necessary in determining the smallest temperature variations detectable. First, what is the minimum amount of time-varying radiation detectable in the presence of the general radiation of the tire. Secondly, what time-variation is caused by the regular tread pattern as the tire rotates. The first question is straightforward and we learn from measurements made on InSb detectors that they have the ability to detect 7-micron radiation at room temperature with a D* in excess of 3 x 10^8. This will allow observation (with a S/N = 1) of a ΔT of $1^\circ C$ in a 1/2-inch area on a tire rotating at a rate equivalent to 60 mph speed. The sensitivity of the detector can be increased by 10^2 with detector cooling. Integration of the signal over multiple scans also enhances the signal-to-noise ratio.

The second consideration is the signal produced by regular variations in the tire (such as the tread pattern), and how this background affects the detectivity of the system. The response to such a regular pattern depends on the size of the system's spatial resolution element in relation to the spatial period of the regular pattern, and on details of the weighting function defining the resolution element. General treatments are available, but we can see by relatively simple arguments that for a gaussian resolution function and a modulating signal of constant spatial frequency f, the response can be written:

$$\int_{-\infty}^{0} \mathrm{EXP}\left(-s^2/C^2\right) \cos^2 (2\pi f s + \theta)\, ds + \int_{0}^{\infty} \mathrm{EXP}\left(-s^2/C^2\right) \cos^2 (2\pi f s + \theta)\, ds = \frac{\sqrt{\pi}}{2}\, C \left[1 + \mathrm{EXP}(-4\pi^2 f^2 C^2) \cos (2\theta)\right]$$

showing that if one chooses a resolution length C greater than 1/f, the modulation due to scanning the tire (varying θ) is not only a smaller ratio of the total signal $\frac{\sqrt{\pi}}{2} C$ for large C, but can be much smaller than that which would be obtained from a single tread period. We see that an appropriately shaped resolution function will minimize effects of regular patterns with little loss of resolution for faults.

Here C = resolution length

θ = angle describing position on perimeter

s = dummy variable describing perimeter position

f = spatial frequency

HOLOGRAPHIC INTERFEROMETRY

BACKGROUND

Holographic interferometry is one of the primary NDT techniques being implemented. This method is capable of detecting both large and small variations on the surface of a tire which can be indicative of sub-surface defects such as local disbonds and voids. Furthermore, accurate deformation and "creep" measurements can be made and viewed in real time.

Two conventional holographic interferometry techniques are commonly used in holographic non-destructive testing of tires: 1) double-exposure holographic interferometry and 2) real-time holographic interferometry.

A double-exposure hologram is constructed by taking two exposures on the same photographic plate in a static position with the object being slightly stressed or displaced between exposures. Any variations on the surface of a tire will show up as interference fringes. This technique produces a permanent three-dimensional record of the surface and can be viewed or photographed with a conventional camera when illuminated with visible laser radiation.

In real-time holographic interferometry, a single-exposure hologram is made in its static position. After the photographic plate is developed, the hologram is replaced in its exact original position. The interference between the holographic reconstructed image and the laser-illuminated object is observed. Any variation of the surface of the tire can be viewed in real time. Permanent records at any particular time can be made with a conventional camera. These holographic recording procedures can reveal subsurface defects and structural characteristics of a three-dimensional image of the tire. When a tire is stressed, subsurface anomalies can be detected in the surface topology and can be identified by fringe signatures.

The four common techniques used for stressing pneumatic tires are: 1) application of heat to an inflated tire, 2) change of air pressure within the tire, 3) application of partial vacuum to an unpressurized tire, and 4) natural "creep" of the tire after a pressure change. Of the above-mentioned stressing techniques, the application of the partial vacuum has thus far proven to be the superior method.

A holographic tire analyser is presently available on the commercial market. This instrument was developed by G. C. O., Inc., and is currently being evaluated by such companies as Uniroyal, Goodyear, and General Motors. The present GCO instrument evolved over the past four years from an instrument that applied stress by changing the tire pressure to the present PT-12 model. This model uses a partial vacuum as the stressing mechanism and holographs the interior of the tire. Using this stressing technique, only the surface above the subsurface separations is deformed, thus reducing the number of false alarm signatures. Holographing the interior of the tire tends to reduce false alarm signatures produced by "creeping" and other insignificant rubber surface effects. The GCO PT-12 is capable of inspecting up to 12 tires per hour.

Negotiations are now underway to procure one of these units so that this instrument and technique can be evaluated. Hopefully, a complete understanding of the type of defects and their holographic signatures will be understood by the time the tire analyser arrives.

LABORATORY PROGRAM

Laboratory activities have been directed mainly to the construction of a holographic facility to inspect in-house, fabricated, rubber-cord specimens. These specimens have built-in known defects and provide a means for determining the types of defects that can be detected using this technique. A study is being made to determine the signatures of various defects. The stressing mechanism being used is a partial vacuum so that the stress will be similar to that placed upon tires in the GCO, Inc. tire analyzer.

Double-exposure holograms have been made of specimens fabricated in-house. These specimens were stressed between shots by hot air heating. The holograms showed fringe patterns where stresses occurred, but were not of good quality. Tests showed that ambient vibrations, air currents, and other environmental perturbations were responsible for the inferior quality of the preliminary holograms. The problems are not serious and are being corrected.

Double-exposure holograms have also been made of specimens using partial vacuum stressing. Initial data indicate that the technique responds only where a disbond occurs. The bisbonds could be induced by plunger tests or other types of trauma. The data are preliminary and must be treated as such. Additional samples having both pre- and post-fabrication defects are being produced in-house to determine the type and size of defects that can be detected.

ULTRASONICS

Ultrasonic non-destructive inspection techniques are based on the propagation of elastic waves into the object to be tested. Such waves are reflected by discontinuities in physical properties, particularly by changes in elastic modulus or density. Therefore, they are specifically sensitive to voids and delaminations. Since the propagation times for ultrasonic signals lie in the microsecond regime, reflection signals can readily be resolved in time to pick out reflections from interfaces at specific depths in the laminar structure. Hence, ultrasonic reflection measurements have unique potential for testing the status of the bonds between layers. It is also easy to measure the thickness uniformity of tread stock and of tread and ply splices. Since ultrasonic techniques measure physical properties of materials, it is entirely possible that ultrasonic signals reflected from the laminar interfaces in tire tires will be significantly modified by fatigue processes which are known to produce subtle changes in composite microstructure and chemical composition.

A broad survey of physical acoustic techniques for non-destructive inspection of tires has been prepared under this program and is being published as a separate document. The paragraphs to follow summarize the principal conclusions of that survey, with emphasis on high-resolution reflection techniques. Such techniques will provide the maximum practicable amount of information to characterize observed defects, and hence are considered most appropriate for the planned effort to correlate NDT results with data from tire section analyses and failure experience.

BACKGROUND

Ultrasonic techniques have been extensively developed and widely applied in the metals industries, usually for the detection of "flaws" (i.e., small voids and inhomogeneities, such as casting bubbles, cracks, etc). The Nondestructive Testing Information Center of the U. S. Army Materials Mechanics Research Center cites over 6000 references to ultrasonic testing techniques and associated technology, but only two of these deal specifically with applications to tires. Visits to three of the largest tire manufacturers (Goodyear, Uniroyal, and B. F. Goodrich) revealed that not one of these currently utilizes ultrasonic inspection techniques, even as a research and development tool, much less for quality control in production. Various industry representatives indicated their companies had "looked at" or "tried" ultrasonics at some point, but specifics of the techniques employed and the objectives sought were not available. Since ultrasonic techniques are ordinarily carefully optimized for specific applications (through choice of frequency, wave type, transducer characteristics, signal conditioning, display technique, etc.,) it is possible that some disappointment may have resulted from cursory attempts to apply metals-oriented techniques which were far from optimum for the tire problem.

One barrier to the adaptation of well-established ultrasonic pulse-echo techniques to tire inspection has undoubtedly been that the fundamental data produced, the original reflection oscillogram (termed an A-scan presentation) is very complex and is not as easy to interpret in terms of structural defects as, for example, an X-ray photograph. In the usual applications, interpretation is aided by image-type graphic displays produced by a facsimile recorder synchronized to a mechanical scan of the object being inspected. In a "C-scan" recording, reflection amplitude is plotted as a gray scale (i.e., print density), versus two mechanical scan coordinates to produce a surface mapping of defect location and severity. In a "B-scan" recording, one axis of the chart corresponds to the acoustic travel time, and hence to the depth below the surface from which reflections are received, so that the display maps a cross section of the object taken along a single line of mechanical scan.

In efforts to demonstrate the usefulness of ultrasonic techniques for tire inspection, it has not been possible to fully exploit such display techniques, because of the lack of a specialized mechanical scanning system capable of accommodating the nongeometric and variable cross-sectional shape of tires.

The section on future plans will outline our approaches to design of an ultrasonic inspection system which will produce useful C-scan and B-scan recordings from tires. However, we will first briefly review certain prior work and present the principal results and conclusions of our laboratory investigations of the reflection signals from actual tire structures and from rubber/cord composite specimens made in our laboratory.

PRIOR WORK

At Southwest Research Institute, under an Air Force contract, an immersion system for inspection of aircraft tires was constructed. This system measured through-transmission of pulses from a transducer inside the tire to another outside. The acoustic beam axis of this transmission measuring system was slowly rotated (through angle ϕ) about a central point in the tire cross-section to scan the tire surface from bead to bead, while the tire was rotated more rapidly about its normal rolling axis to scan with respect to the angle coordinate θ. Automatic gain control was employed to nullify the variations in transmission caused by the normal variations in the thickness and structure of the tire encountered as the ϕ-scan progressed from the tread region to the shoulder, sidewall, and bead areas. More sudden decreases in transmitted amplitude occured as acoustically opaque regions (attributed primarily to separations) were carried through the transmission path by the θ-scan rotation, and detection of defects was based on counting pulses that dropped below a fixed percentage of the running average amplitude.

According to Ref. 1,there was poor correlation between this system's indications and actual tire failure experience. Verbal reports indicate that further experience with this system obtained at NBS has been similar.

The SRI system was designed on the presumption that the principal fault to be detected was the separated delamination. Their system calibration work makes it clear they succeeded in designing a system which would reliably detect such defects down to 1/4 inch in diameter. Hence, the failure to obtain better correlation with tire performance must be ascribed to inadequacy of the initial assumption as to the dominant role of separations in causing tire failure.

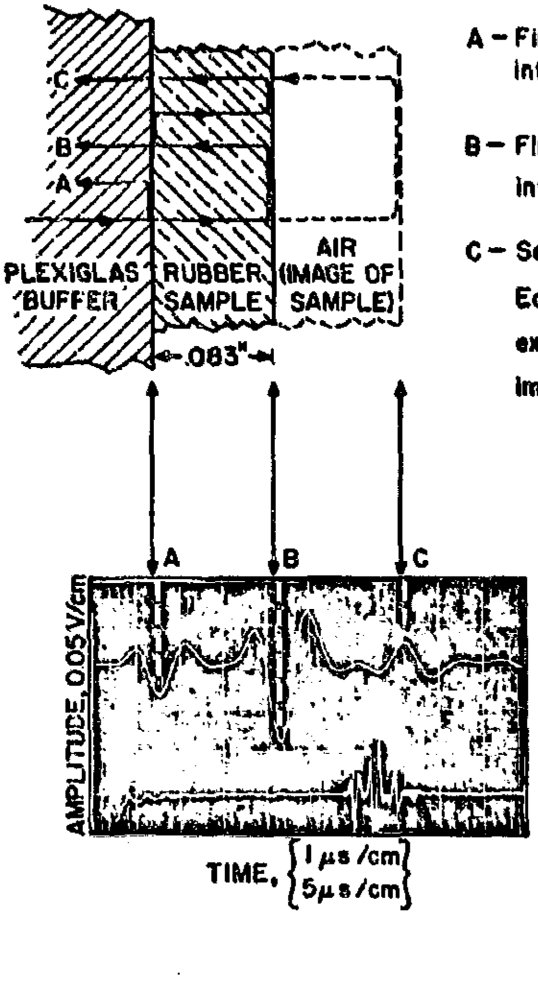
G. H. Halsey is widely known as a proponent of ultrasonic techniques for tire inspection. In business for himself at the Scientific Testing Laboratory, he has sought to sell testing services and/or instrumentation in this area to the tire industry. Thus far he has not succeeded in this endeavor on any significant scale. In conjunction with Smithers Laboratories, and supported by several rubber companies (unnamed), he has investigated the correlation between ultrasonic inspection results and tire service performance, but reports of this work are being held proprietary by the sponsors.

In a 1967 paper, Halsey discusses certain techniques and provides a number of useful suggestions. He recommends monitoring the reflection from the tread rubber to carcass rubber interface as a means of detecting incipient tread separation. He suggests that time measurements on reflection signals can serve to assess tread thickness uniformity and splice quality, and that these factors are vital to tire safety as well as to ride comfort. Acoustic impedance variations ascribable to changes in cord tension are said to be detectable.

LABORATORY PROGRAM

Laboratory experiments have been performed to explore the nature of the reflection signals returned from the normal laminar structure of tires and from rubber/cord composite specimens made in our laboratory. This section summarizes the principal results and conclusions of this work, incorporating selected data as necessary. This work has been limited to spot-to-spot observation of reflection oscillograms. Plans for developing an immersion scanning facility are discussed in the following section.

One objective was to make an experimental assessment of factors determining the optimum test frequency. Using highly dampened transducers shock-excited by a narrow DC pulse, representing the present commercial state-of-the-art, the duration of the acoustic output pulse is about twice the natural period of the transducer. Allowing for the two-way travel delay, reflections in a laminar structure can be clearly resolved, provided the reflecting interfaces are separated by a distance approximately equal to the acoustic wavelength. In tire rubber, the wavelength is approximately 1.6 mm (about 1/16 inch) at a frequency of 1 MHz. Figure 4 demonstrates clearly resolved reflections from the front and back surfaces of a 0.083 inch (2.1 mm) thick sheet of carcass rubber, obtained with a 1-MHz transducer. Figure 5 shows reflection signals obtained in the 6-ply tread region of a double-belted tire, using 1-MHz and 5-MHz transducers. In either case, the echo signal is of generous amplitude (measurable in millivolts) for the



A – First return from plexiglas/rubber interface

B – First return from rubber/air interface

C – Second round-trip in sample – Equivalent to return from non-existent interface at C, the acoustic image of A in B

Figure 4. Reflections From Single Layer Of Carcass Rubber

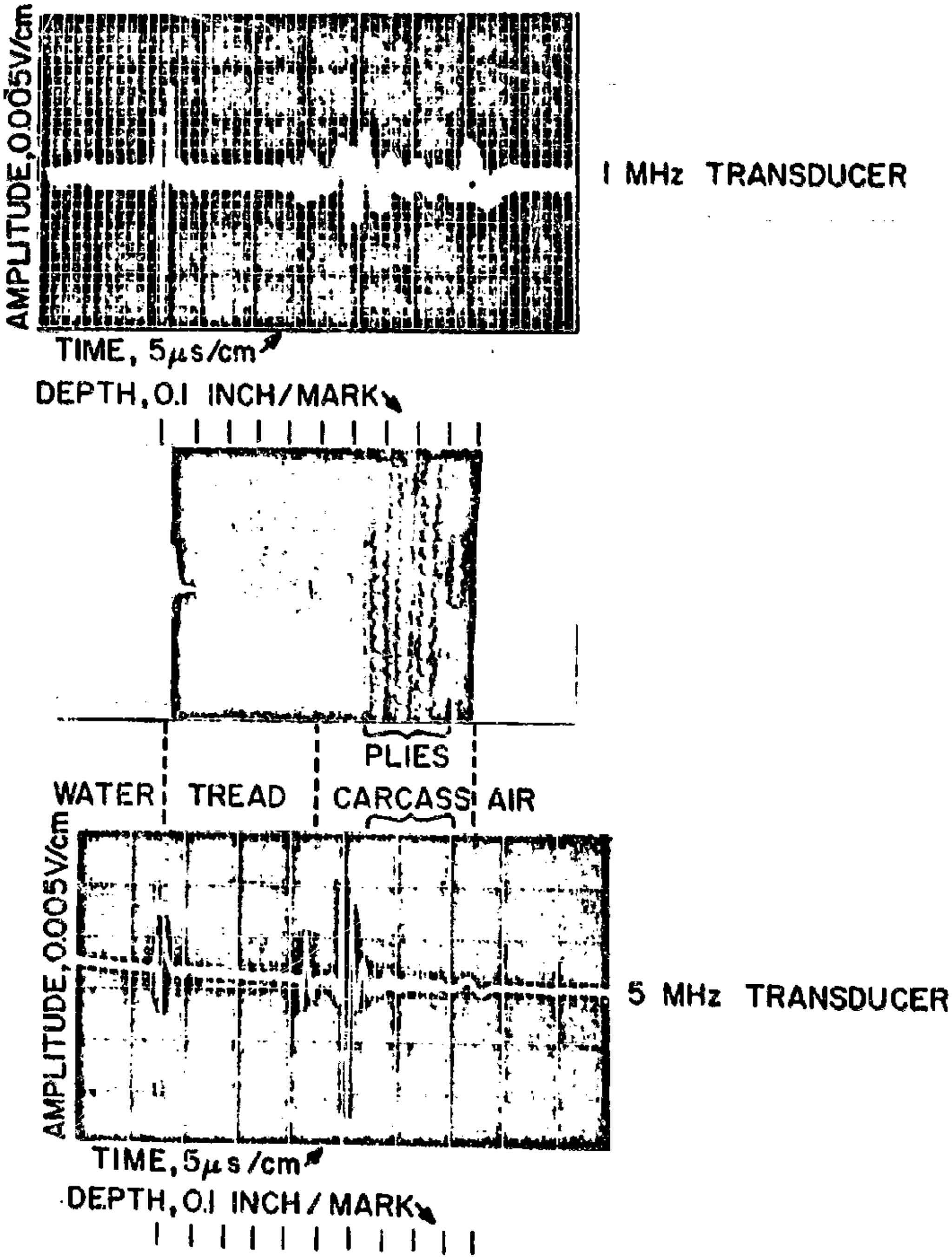


Figure 5. Reflection Signal Matched To Tread Structure Of Belted Tire Section (TS4)

reflection from the inside surface of the tire. (The acoustic pulse must pass twice through the entire thickness of the tread region. Thus, even the 5-MHz transducer frequency is not too high for practical use; however, most of the high-frequency content of the 5-MHz signal is taken out by the first ply reflection, and enhanced resolution is obtained only in the tread-stock region ahead of this reflection. In neither case are the reflections from the deeper ply layers clearly resolved from each other; however, a separated delamination would give a reflection signal large in amplitude compared to ply signals at the same depth. In this event, the depth resolution would certainly be adequate to determine which interface had come apart. Figure 6 illustrates this point for a disbond in a two-ply slab specimen. Figure 7 shows how a reflection from a selected depth can be gated out in order to monitor it for evidence of poor bond at the corresponding interface. Figures 8 and 9 confirm the expected fore-shortening of the time scale and gross changes in amplitudes for reflection signals observed in the thinner sidewall and in the more strongly curved shoulder regions. In scanning the entire surface of a tire, such changes in amplitude must scan-programmed or accommodated by AGC. Also, the time windows employed for gating out the reflections from interfaces of interest must be referenced to other reflections, or even to the reflection being examined. While these necessities introduce additional complexities not commonly provided for in commercial ultrasonic instrumentation, the required electronic techniques are well-known and straightforward.

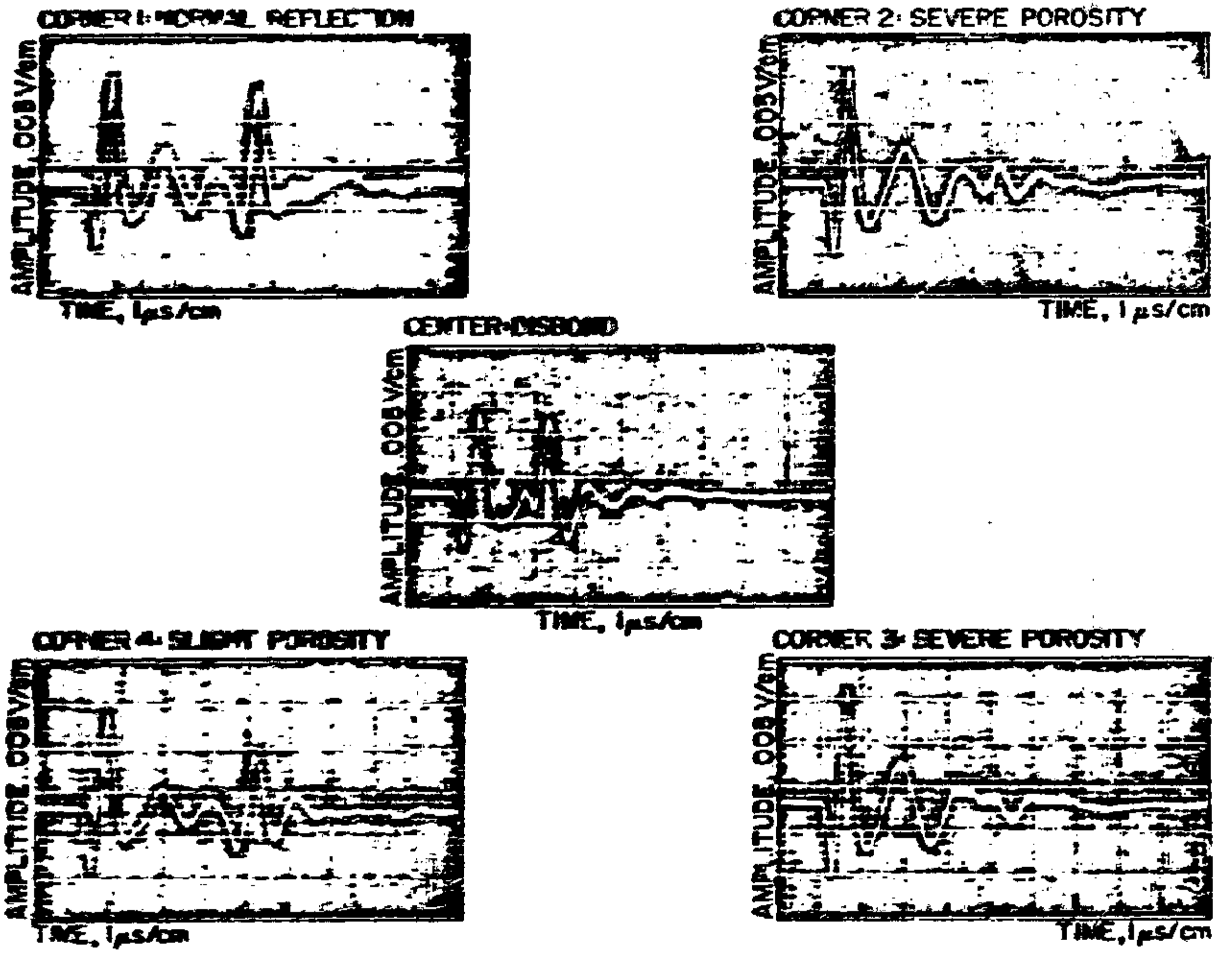


Figure 6. Comparison Of Reflection Signals At Four Corners And Center Of Slab Sample S15 (5 MHz Transducer, 2" Plexiglas Delay Buffer)

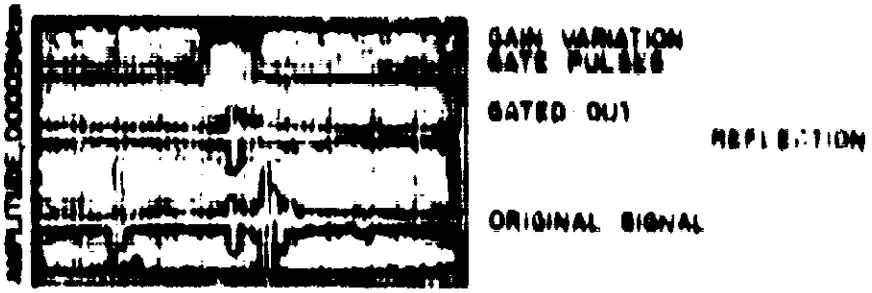


Figure 7. Gated Out Reflection (TB4, 5 MHz Transducer)

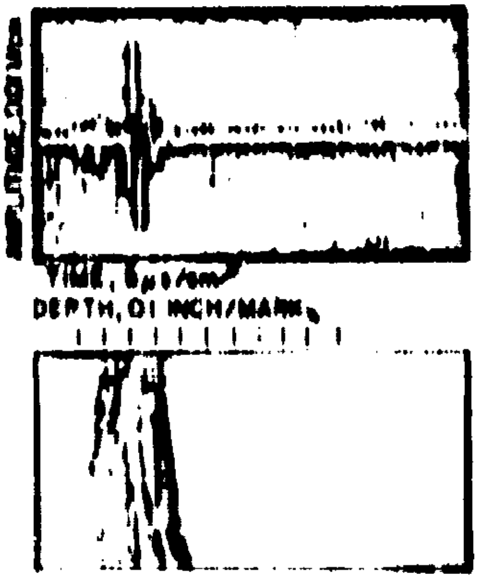


Figure 8. Reflection Signal Matched to Side Wall
Structure (1 MHz Transducer, TB4

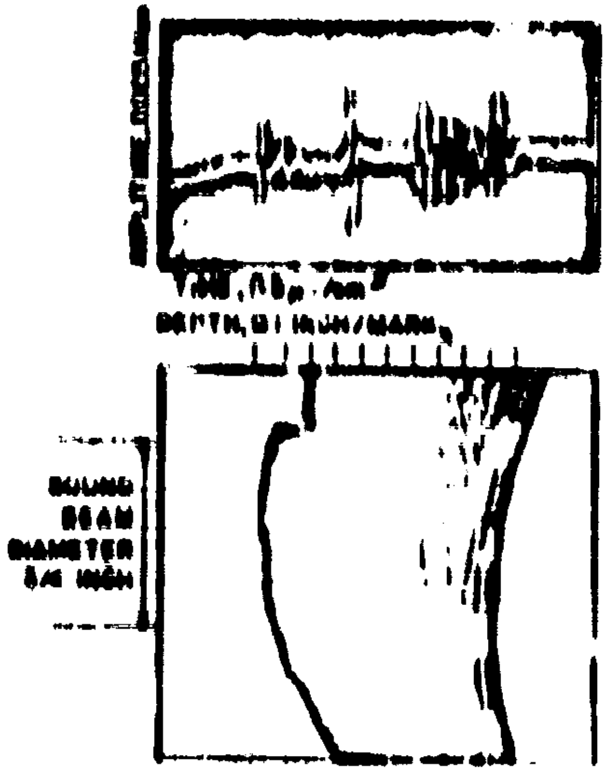


Figure 9   Reflection Signal Obtained in Simulated Structure (5 MHz Transducer, [illegible])

In a simple laboratory experiment, the feasibility of acoustic impedance matching to the tread rubber was demonstrated using a weak solution of polypropylene glycol in water as the acoustic coupling fluid. By adjusting the concentration, the reflection at the interface between the glycol solution and the tread rubber was easily made to disappear completely. While certain obvious practical questions require investigation (such as the degree of variability of tread rubber impedances, stability and cost of acoustically suitable solutions, etc.) it is expected that such acoustic impedance matching will reduce the level of interference from surface relief features such as the tread pattern and sidewall lettering. Matching also should help to reduce variations in the reflection amplitudes in the shoulder region where the normal to the ply layers pass through the outer surface of the tire at a considerable angle.

PLANNED IMMERSION SCANNING SYSTEM

An immersion scanning system for ultrasonic tire inspection is planned that will differ in several important respects from systems previously reported:

1. The tire will be laid flat in the horizontal plane and totally submerged. It is expected that this procedure will eliminate difficulties due to entraining air bubbles in the tread pattern reported to have been a problem when the tire is mounted vertically and rolled into and out of the coupling liquid.

2. Reflection techniques employed will permit specific layer interfaces in the tire structure to be monitored for bond integrity and fatigue degradations. For the small changes in acoustic impedance assumed to be associated with

weak or degraded bonds, reflection measurements are inherently more sensitive than transmission measurements. The impedance transitions in a tire structure are small to begin with; therefore, at any given interface, the reflection coefficient R is small, while the transmission coefficient $T = 1-R$ is large. Under these circumstances, $\Delta R/R$ will generally be much greater than $\Delta T/T$.

3. Tires will be mounted and inflated for testing, offering the possibility that defects in cord structure may be detectable through changes in acoustic impedance with cord tension, as suggested by Halsey. Furthermore, an inflated tire offers an increased likelihood of observing any delaminations induced by (or aggravated by) leakage of air into the ply structure.

4. The system will include a C-scan capability with a proportional gray-scale indication of defect severity. It will thus not be limited to a prior decision as to a severity criterion for defect detection. It will be possible to observe subtle indications of defects, and to search for correlations with service performance.

5. A B-scan capability will be provided that gives a simultaneous indication of the thickness uniformity of all layer elements in the tire structure.

The present plan is to design and assemble a tire scanning system utilizing commercially available subsystems and components. A conventional submersible turntable will be adapted to hold the tire submerged in a horizontal plane, and to rotate it about its usual rolling axis. A mechanism will be designed for scanning from bead-to-bead. The transducer will move around the outside of the tire section on a C-shaped circular rail, the center of which coincides with the center of the tire cross-section. The spot on the tire surface being examined will be defined by angle coordinates ϕ and θ. The special ϕ-scan mechanism will be designed to mount to this manipulator system, so that the linear translation motions it provides can be used to position the center of the primary arc in the desired relation to the tire cross section.

A facsimile type graphic recorder can be synchronized with the θ and ϕ motions to produce a C-scan presentation. The facsimile recorder prints a tone shade density proportional to the current passed through a damp electrolytic paper.

For the C-scan presentation, the horizontal motion of the stylus will be slaved to the θ-rotation of the tire, and the chart paper advance will be slaved to the ϕ-scan. The printing current (and hence chart tone density) can be made to correspond to any single parameter derivable from the A-scan reflection signal. For example, the chart density can be made proportional to the amplitude of the reflection from some interface (e.g., tread/carcass, first ply, etc.), or from the reflection amplitude within the whole ply region.

The unit could also be used in a B-scan mode where the horizontal line-sweep of the recorder stylus will correspond to the acoustic round-trip travel time, and hence to the depth of the reflecting interface. The chart paper advance will correspond to one of the mechanical scan coordinates on the tire, the other being held fixed. A B-scan versus θ (with ϕ = constant, for example, at tread center), should produce uniform parallel lines for a perfect tire. Any non-uniformities in tread thickness or poor splices will be readily apparent. A B-scan versus Ø (with θ = constant) will show a flattened cross-section diagram from which one can assess sidewall thickness, belt centering, and symmetry of other components.

SECONDARY NDT METHODS

This section describes several additional NDT methods to receive a lower priority of investigative effort. In comparison to the previously described primary methods, they either measure additional tire parameters or show some promise of measuring the same parameters more economically. They are not considered as pivotal to the prime task of defining the anomalies or defects that correlate with tire failure, but it is felt they have potential benefit to the program.

LIQUID CRYSTALS

Liquid crystals, as their name implies, are a class of materials that exhibit the characteristics of a liquid and have the order of crystalline materials. The heat-sensitive cholesteric liquid crystal molecules are used for thermography. The operating temperature range of thermal sensitivity is adjusted by properly compounding several different materials. Throughout this thermally sensitive range, the liquid crystal material is highly bi-refringent. This gives rise, through selective reflection, to the characteristic coloring of red, green, and blue, representing the low, medium, and high parts of the thermal range. One distinct advantage of liquid crystal techniques over infrared imagery is the elimination of possible variation in emissivity of the surface.

While the application of liquid crystals to thermography is a rapidly expanding area, only one instance of its application to tires has been reported. This early work by the Goodyear Tire and Rubber Company was discouraging. The liquid crystal material used was found unacceptable because of its inability to remain on the tire during exercising.

A limited investigation into the application of liquid crystals for tire thermography was done in our laboratory. Flat rubber/cord samples with disbonds were coated with liquid crystals to determine the method's ability to detect the disbond and to determine the effect of rubber on the liquid crystal compound. Heat applied either behind the sample or in front of the sample was adequate to demonstrate that disbonds were easily detected. Contamination from the rubber limited the lifetime of the liquid crystal. At least two possible solutions exist to this problem. The most desirable is to use encapsulated liquid crystal material. The second is to provide an impermeable membrane between the rubber and liquid crystal material. The latter approach was implemented by means of both thin teflon tape and polyvinyl fluoride film. The liquid crystal used during these experiments was compounded using two parts (by weight) of cholesteryl nonanoate to one part cholesteryl olyel carbonate. This compound provided a mean temperature of operation of 45°C. with a range of 5°C.

Encapsulated liquid crystals with an operating temperature of 85°C. and a range of 10°C. are being procured for routine visualization of the temperature distribution of tires being exercised. The tire being exercised is easily viewed and photographed in stop motion by using a strobe light synchronized to the tire rotation. It is intended that this approach be used as a backup to the infrared method.

DYNAMIC FORCE AND ACOUSTICAL VARIATION

Most of the non-destructive test methods considered are capable of measuring a limited number of tire structure characteristics. None of the tests attempts to measure the dynamic characteristics at typical highway speeds and deflections. Since tires cannot be considered as truly linear devices, it follows that high-speed characteristics may provide a useful insight into tire mechanics. This method is being considered in work at the National Bureau of Standards, where the dynamic force variation of tires operating at designed loads and speeds up to 70 mph are being determined. If this work continues to bear results, data obtained from it correlated with data obtained by other NDT methods will be beneficial.

Current force variation measurements are made by measuring the variation in the radial and tangential force on a roller as the tire rotates. The total force, measured by a suitable transducer, and its harmonics are recorded for one tire rotation. The radial component can easily vary by more than 3% of the static force. At higher rotational speeds, part of this energy must be emitted in the acoustical spectrum. Thus, relatively inexpensive acoustical detection and analysis equipment may provide an alternative method of measuring relative force variations caused by nonuniformity of tire structures. This approach would have the distinct advantage of being usable during wheel or road tests. In addition, the audio method would be usable at higher frequencies than is practical for currently used systems for which the frequency response is limited by the mass of measuring system components. Investigation of this method will determine its feasibility. The necessary equipment to rotate the tire to 20 mph and to collect and analyze the acoustical data is available.

RESONANCE TESTS

Preliminary investigations into tire resonance testing were performed by James Weigl at Massachusetts Institute of Technology in partial fulfillment of the master's thesis requirement, under the technical direction of Professor David Wilson. The reported results that cord cuts of 1/4 inch and larger were detectable in either bias or radial tires is of particular interest. In addition, it was reported that the resonance frequency and Q are functions of inflation pressure and tread depth. The results, while very encouraging, must be considered as inconclusive at this time because of the limited number of tires so far tested.

Based upon the preliminary work and upon discussion with Professor Wilson, it appears that a properly developed test could be made selective either by controlling some of the independent variables, or by secondary measurements. This would allow selective evaluation of such factors as cord integrity and rubber/cord hysteresis, provided such parameters as tread depth and inflation pressure were separately measured or controlled. The promise of resonance testing and the lack of acceptable methods for rapid nondestructive evaluation of cord integrity and rubber/cord hysteresis make this an important area for future work.

A limited project is being supported by MIT to further investigate this testing method. The investigation will involve designing and building the necessary experimental test equipment to minimize the effect of experimental variables and to perform the necessary experiments to obtain a better understanding of the technique. Future efforts in this area will depend upon the results of the current phase.

MICROWAVE TESTING

Microwaves have been used for some time in nondestructive testing of materials. The efficacy of this method depends to a large extent on the dielectric properties of the structure that is being inspected. Interfaces between materials of different dielectric constants cause reflection of the signal, and may thus be used to indicate anomalies in construction or imbedded objects or impurities.

In one method of microwave testing, the sample is placed in one arm of a microwave interferometer, and phase and intensity changes in the reflected signal are detected. This technique is limited in that slowly varying nonuniformities that are not defects are difficult to distinguish from smaller, more singular defects. In addition, irregularities of shape produce signals similar to those of small singular defects. Preliminary measurements made at 50 GHz suggest that these techniques using an active source are limited in their application to tires.

A second technique is the use of microwave radiometry. As the microwave frequency decreases, the skin depth increases. This enables one to increase the meaningful depth of penetration. In infrared radiometry, a major problem lies in the necessity for the internal friction to change the surface temperature of the tire, since the rubber is opaque to the infrared radiation from the internal source. We must then distinguish between irregularities in frictional heating occurring very close to the surface, and irregularities in heating due to faults in the deeper lying cord structures. A hybrid system would use a microwave radiometer at 10 cm. to detect the heat from internal sources. Here, the tire is relatively transparent to this radiation, and one can detect the radiation produced at the fault as compared to the lesser intensity radiation produced at the same depth in the normal tire structure. The equipment for this experiment is in-house and will be used to determine the feasibility of this approach. The same tire exerciser used in infrared testing will be employed. This equipment is capable of loading the tire to 500 pounds at 20 mph. Tire deflections equivalent to full load are obtained by decreasing tire inflation pressure.

RECOMMENDATIONS

The paragraphs below outline plans for specifically recommended further work in a program designed to assess the contributions that non-destructive inspection methods can make to tire safety:

1. An inspection program will be carried out on new tires that will then be subjected to wheel and road tests. Non-destructive inspections will be performed by radiographic, visual, infrared, ultrasonic, and holographic methods. Failed tires will be analysed to determine the causes of failure. The purpose of this program is to furnish comparative data relating indications of the same singularities by each of the non-destructive inspection methods, and to furnish data relating actual tire defects and tire failures to such indications.

2. Other promising non-destructive testing methods will be developed to augment or replace existing methods. Priority will be placed on methods suitable for screening tires prior to compliance testing, and for inspection prior to recapping.

3. An understanding of tire materials will be developed and maintained. Laboratory samples will be fabricated and tested to permit studies of defect propagation and tire failure. Such work will provide the necessary background for meaningful failure analysis on previously inspected and exercised tires.

4. An infrared sensor will be installed and maintained at the compliance test center to study the changes in infrared signature that occur during wheel testing.

5. The usefulness of radiographic inspection for sample screening and quality assessment in connection with compliance testing will be investigated.

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