Surface Inspection on Optical Disc Media

C.G. Daley, Automatic Inspection Devices, Inc., Toledo, OH

Keywords: Compact disc; Surface characterization

ABSTRACT

A.I.D. Inc. has played an active role in the area of optical disc inspection since 1986, and has developed a series of systems for use with audio CD's. With the advent of higher speed requirements in production technology, and the emergence of interest in video, WORM, and MO discs, A.I.D. has been developing systems that afford higher speeds, improved resolution, and better defect classification. In addition, A.I.D. has designed systems to meet new optical disc requirements, including bar code readers, catalog ID systems, and disc counters. The systems and their capabilities are described, as are the requirements that future systems will have to meet. Also, some limitations on inspection by optical methods are briefly discussed.

INTRODUCTION

Recent publications [1, 2] have described the operation and capabilities of A.I.D. systems designed for the on-line inspection of audio compact discs. These systems are based on a direct imaging principle using linear array CCD cameras and white light, and are able to detect the presence of such flaws as bubbles, black specks, scratches, dents, and coating pin holes - in short, any defect which causes the interruption or deviation of a light ray - in sizes as small as 40 µ. In addition, the systems are able to measure disc eccentricity, coating reflectance, birefringence due to stresses in the substrate, and disc warp.

In normal operation, the systems inspect each CD for localized defects and mirror band eccentricity in approximately 2 seconds. Periodically, discs are also inspected for global birefringence, warp, and coating reflectance by a process that adds about 0.4 seconds to the inspection time. The reason for this sampling approach is that these quantities tend to be correlated with process conditions, and to vary somewhat more slowly and systematically than localized functional and cosmetic defects. Since the system is automated under software control, the periodicity of this additional inspection can be user specified by simply entering a “disc skip” parameter.

As the audio CD industry has matured over the past few years, increased demands have been placed on inspection systems, particularly in the areas of increased throughput and lower cost. In addition, the need for in-line reading of disc bar and alpha numeric codes has become apparent, as has the need for the automated counting of discs on production spindles. In related areas, new technologies in the areas of optical video discs and writeable media such as WORM and MO discs have been rapidly emerging, and each of these places unique requirements on automated inspection systems. The combination of higher resolutions for defect detection and faster throughputs for inspection is a common denominator for all of these technologies. In addition, some - particularly those involving writeable media - require that the source wavelengths and wavelength distributions be selected with care.

Since the video and writeable disc technologies are in their relative infancy compared to audio CD technology, the defects of greatest interest are not as well defined at present. Clearly, some of the defects of concern to audio CD fabricators will be of similar concern in the new technologies, but there is already substantial evidence that more stringent requirements will be placed on both the qualitative and quantitative nature of these and new defects. These requirements will obviously become more clear as experience is gained with production in these new areas.

The present paper reviews some of the new developments in these areas that are presently underway at A.I.D., and outlines some of the near- and longer-term capabilities that inspection systems will probably have to meet. In many cases, substantial developments in optics, microprocessor hardware, and software will be necessary, but at present, all appear to be comfortably within the state of the art for these areas. The paper also discusses briefly some fundamental limits on the ability of optical inspection systems to achieve increasingly higher degrees of resolution for defect detection.

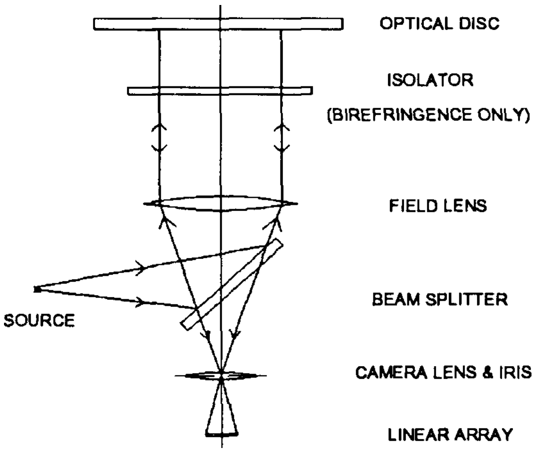


Figure 1: Optical system

AUDIO DISC INSPECTION SYSTEM

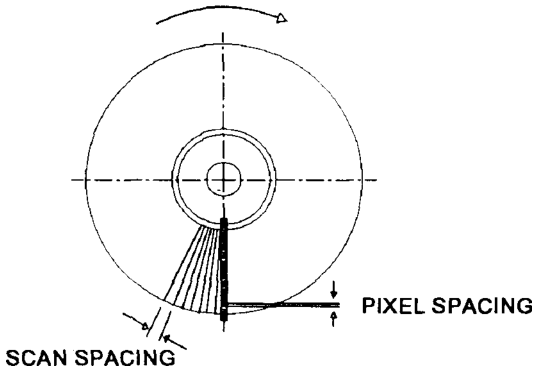
Optical System

As discussed in references 1 and 2, the optical front end of A.I.D. inspection systems consists of a telecentric optical arrangement and a “white light” source, as illustrated schematically in Figure 1. Such a source has the advantage of being inexpensive and easy to maintain, and offers lifetimes in the neighborhood of 1,000 to 2,000 hours. Even though the source is relatively broad band in its distribution of wavelengths, the effective spectral width is only about 150 nm (gaussian full-width basis) after the light passes through the optical system. The center of the spectrum is at 630 nm, and while CDs are actually read at 780 nm, the use of the shorter wavelength for inspection causes no obvious problems in the case of audio compact discs. The inspection device normally has two optical channels like that shown in Fig. 1: the birefringence channel includes the isolator shown, and employs a 512 pixel linear array camera. The defect channel is similar, but uses a 1,024 pixel camera and does not include the isolator. For systems designed to discriminate between pin holes and other defects, a collimated light source is also placed above the disc; when a pin hole is present, light from this source passes through the hole and into the camera below. This same overhead lamp becomes the main light source for clear substrates, which can be inspected by the same system.

The camera iris is adjustable, with higher f-stop values generally serving to improve the optical contrast of defects. At the same time, however, higher f-stop values also increase the sensitivity to disc warp, and in many cases this sensitivity can become excessive for coated discs. In practice, a common working value is f 5.6. The system is not sensitive to warp in uncoated discs, however, and so the f-stop can be increased to much higher values for such inspections.

EXACT 360 DEGREE ROTATION

Figure 2: Pixel and scan spacing



The linear array camera is arranged so that the disc is scanned radially, as shown in Figure 2. The disc is mounted on a stepper motor driven spindle, which rotates the disc over the camera in a user-selected number of steps. Since the field of view for the camera is about 1.5 inches on an audio disc, the pixel-to-pixel resolution is approximately 40 μ. Best results are obtained when the scan-to-scan resolution is comparable, and this condition determines the number of steps in the rotation. In most cases 6,250 steps are used for audio discs, and this gives a scan-to-scan spacing of 60 μ at the outer edge of the disc; the corresponding spacing at the inner mirror band is about 20 μ.

Defect Inspection

A typical audio disc inspection takes just under 2 seconds to perform, and consists of 6,250 scans of 1,536 pixels each (defect plus birefringence camera) - or 9.6 million scan-pix-

DEFECTS AND THRESHOLDS

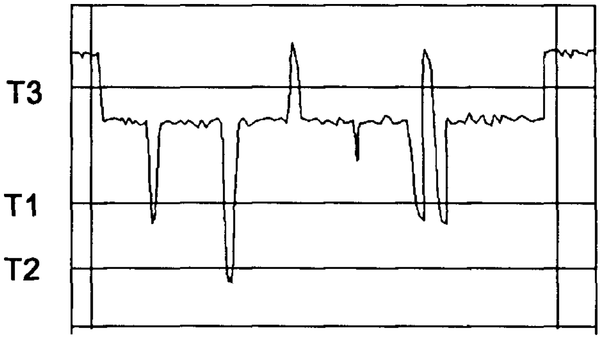


Figure 3: Typical defects and thresholds

els - which are sent to the microprocessor from the camera. The processor operates at 12 MHz. One of the reasons that the inspection can be accomplished so quickly is that most of this information is in fact discarded - that is, only the information related to the presence of a defect is actually processed. Figure 3 illustrates how this can be accomplished: the system makes use of three thresholds (T1, T2, and T3) for the defect channel, and a fourth (T4) for the birefringence channel. In the absence of a defect, none of these thresholds is crossed, and the system detects no defect "hits". In the presence of defects, thresholds are crossed according to the type and severity of the defect. For example, black specks and bubbles are usually severe functional defects with high optical contrast and cause the reflected signal intensity to drop below T2. Cosmetic defects like dents and scratches, on the other hand, are less severe and usually cross only T1. Pin holes in the coating allow light from the overhead source to pass to the camera, resulting in a T3 crossing; shiners, which generally exhibit a higher reflectance than the data area, exhibit similar behavior.

Severe defects like bubbles and black specks are often accompanied by local regions of high stress which can be detected as T4 crossings in the birefringence channel. Such crossings are signatures for the defects, and can be used for further defect differentiation.

Fortunately, most acceptable audio discs are "dilute" data systems in the sense that only a few of the 9.6 million scan pixels need to be processed as threshold crossings. When a crossing does occur, the distance between the negative and positive going T1 crossings is processed as a measure of the defect size. Since most defects actually persist over multiple scans and pixels, it is necessary for the software to accumulate this information in a way that an overall defect size can be determined. Such a process is not necessarily straightforward, since a defect that appears to the eye as a single large flaw might, on a microscopic level, actually be a collection of much smaller defects. To deal with such cases, the processing algorithms include connectivity routines whose purpose is to aggregate these small regions into a larger whole.

Gray Level Inspection

As was mentioned previously, global birefringence, warp, and coating reflectance are not usually measured on every disc inspected, but rather at intervals (every nth disc) that can be specified by the user. One of the reasons for this is that these characteristics tend to change systematically with process conditions, and therefore relatively slowly compared to typical production rates. This is fortunate, because unlike defect inspection for which much of the scan data can be simply discarded, the measurement of global birefringence, warp, and reflectance requires that all of the scan data be retained in gray-level format. Such a process is significantly slower than looking only for threshold crossings, and can add considerable time to the overall inspection process.

In practice, only a few gray-level scans are made. The user selects 4, 8, or 16 equally-spaced scans, so that the disc is actually sampled for the three quantities of interest. This is generally sufficient, since birefringence, warp, and reflectance tend to vary rather slowly with distance. Typically, the user will select 8 scans, which will add about 0.4 second to the overall inspection time.

RECENT DEVELOPMENTS FOR AUDIO DISCS

High-Speed Inspection System

The baseline inspection system is able to scan a disc for defects in 2 seconds, and gray-level inspection adds about 0.4 second to the process. As audio disc throughputs have increased over the last year, so has the need for shorter inspection times. Modern process equipment is now capable of disc-to-disc process times of about 2.5 seconds, about half of which is needed for robotic loading and unloading of the discs - thus, the inspection times required are about 1.25 seconds.

On the one hand, it is a simple matter to shorten the inspection time simply by running the stepper motor drive system at a faster rate. This means that fewer scans are made per 360 degree rotation of the disc, and that the scan-to-scan resolution suffers accordingly. It is far more desirable to maintain an identical or similar scan-to-scan resolution, since only in this way can the user be assured of detecting the defects of interest.

The simplest solution is to increase the operating speed of the microprocessor system, so that similar data rates can be handled at higher speed. This is the approach that A.I.D. has taken with its audio CD system: the camera read-out speed has been increased by 33%, which reduces the scan time from 2 seconds to 1.5 seconds. If the increase in data throughput is combined with a 20% reduction in the number of scans, a scan time of 1.2 seconds is achieved. In fact, the scan time with both modifications is measured to be 1.17 seconds, and repeated testing has confirmed that the slightly higher scan-to-scan spacing (75 µ at the disc edge, 25 µ at the inner mirror band) has introduced no significant loss in the detectability of defects that are of interest to disc manufacturers.

The system has been evaluated using both a fast handling system and a bar code reader (see following section), and disc-to-disc cycle times as short as 2.2 seconds have been achieved.

Even shorter scan times could be achieved by further increasing the microprocessor speed, although there has to date been no call to do so. A fact that should be borne in mind, however, is that faster scan rates must be accompanied not only by increases in data handling capabilities, but also by higher light levels in order to achieve the desired exposure of the CCD devices. No particular problems in this area were encountered in the high speed audio disc system, but it is a factor to be considered as resolutions and speeds increase.

Bar Code Reader

One of the problems encountered in audio disc production is mislabeling - that is, the printing of a label that does not correspond to the recorded material. Such problems can arise for a variety of reasons, but the up-shot is usually mispackaging and shipment, so that even at low levels they are cause for great concern.

All audio discs include an alpha-numeric code that is stamped near the inner mirror band and concentric with the center of the disc, and many (but not all) also include a bar code pattern that is similarly impressed. Thus, devices that can read either or both of these codes can help to eliminate the mislabeling problem.

The bar code is usually easier to read, although the problem is by no means trivial. Standard, commercially available bar code readers are not able to read codes on most discs because of both the optical characteristics and the curved configuration of the pattern.

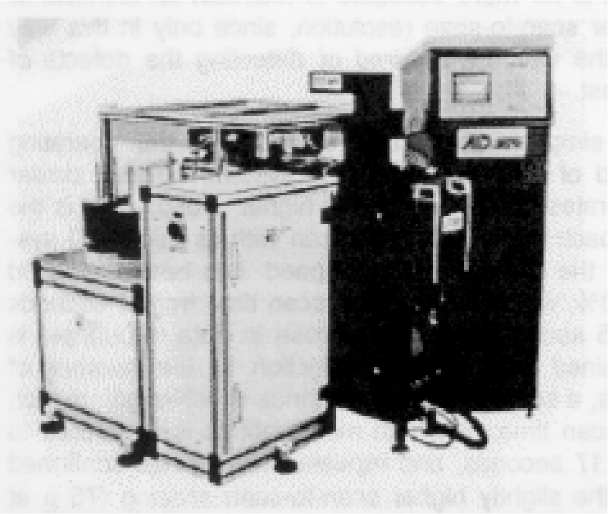


Figure 4: Bar code reader with A.I.D. audio inspection unit and robotic handler

For most discs, the bar code is an alternating pattern of specular reflecting bars and bars whose substructure is an array of tiny dots. The latter behave rather like crude diffraction gratings in that they reflect light in definite directions that depend on the wavelength of the incident light. Other discs can have simpler patterns consisting of an alternating series of opaque and transparent bars.

The curved path of the codes also makes reading difficult or impossible by scanner devices that sweep a laser beam multiple times along a straight-line path.

The approach taken by A.I.D. was to develop a bar code reader that can be used either as a stand-alone unit or in conjunction with an audio disc inspection system. When used with the inspection system, the reader scans the code at the same time that the disc is inspected for flaws, and the result is integrated into the overall acceptance criteria for the inspection. Figure 4 shows the bar code reader mounted on a high-speed inspection unit, together with a robotic handler. As a stand alone unit, the reader simply accepts or rejects the disc. In either case only one rotation of the disc is required for the bar code scan.

As presently configured, the reader employs an infrared LED source which is integrated with a photo detector and amplifier into a compact package. When the unit is used with the inspection system, scanning is synchronized with the same stepper motor drive that rotates the CD, and in the course of one rotation the disc is scanned 3,125 times in the bar code region. This means that the distance between scans is about 44 µ, so that the narrow bar on a typical US 39 code is scanned about 7 times. The same US 39 code has wide bars that are in a 2:1 ratio with the narrow bars, so that these are scanned about 14 times. Since the code is read concurrent with the inspection process, the total read and decision time depends on the speed of the inspection unit. To date, read times of about 1 second have been verified.

The reader operates by comparing the code with a reference code which can be entered either manually via a personal computer interface, or by simply reading a reference disc whose code is known to be correct. The code can be read from either side of the disc, and initial orientation of the disc is not important - that is, the algorithm effectively wraps the circular scanned code region so that even if the read scans begin in the middle of the code, correct identification is possible.

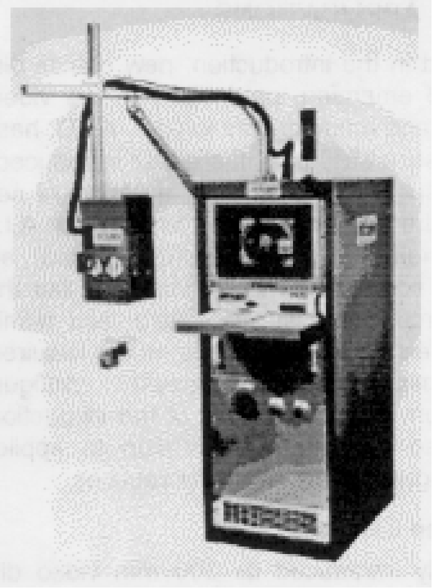


Figure 5: Catalog ID system

The system has been initially configured to read US 39 code whose narrow bar dimension is about 0.012 inch, but other configurations and codes can be read as well. The main issues that must be reviewed are the bar size, the optical characteristics, and the encoding scheme.

Catalog ID System

Whereas not all audio discs have bar codes, all have an alphanumeric code in the same general region of the disc as the bar code. Thus, a catalog ID system, which can read and compare this code with a known reference, can be useful for the same general purposes as a bar code reader. The problem is somewhat more complex than bar code identification, since a greater variety of patterns and comparisons are necessary. In addition, code fonts vary widely throughout the industry, with some being much easier to read and compare than others. A third complicating factor is that nominally “good” fonts can deteriorate significantly in quality as they are transferred from master to stamper to disc.

A.I.D. has recently developed a catalog ID system which is currently being evaluated in a production environment, and which is shown in Figure 5. Based on the use of a 448 x 576 pixel matrix array camera which views the entire hub region of the disc, the system compares the characters read from the disc with a library that contains a reference font. The algorithm is therefore not based on a pattern match approach, but rather on actually reading the characters on the disc. If the characters on the disc in question agree with the user-entered reference code, the disc is accepted.

Like the bar code, each element of the alpha-numeric code is usually composed of an array of tiny dots, which reflect light like a diffraction grating. Thus, the illumination must be designed with care, and must be tailored to some extent to the individual code patterns in use. For the present system, overhead diffuse light is adequate to achieve the uniformity needed for character identification.

In practice, the disc is placed under the illumination head in any orientation by a handler, and a sensor signals the unit to begin the identification process, which requires only 0.75 second to complete. The user has easy access to the system via a track ball device, and can enter the correct reference code by allowing the unit to read a standard production disc. The software allows the user to specify which characters must be verified, and which need not be verified. This feature can be useful if the encoding scheme makes the verification of certain parts of the code unnecessary. In addition, since there are inevitably some codes that the unit will not be able to recognize, due either to flaws or other factors, provision is made for choosing either a pass/fail mode or a pass/fail/uncertain mode.

It is anticipated that as production experience is gained with the system, the applicability can be extended to a variety of coding and font styles.

Disc Counter

Automated counting of compact discs is an application that appears to be somewhat trivial at first glance, but in fact turns out to be rather difficult to accomplish reliably in practice. In most production processes, discs are at some time or another stacked on spindles for movement from one process stage to another. Each spindle can hold approximately 100 - 200 discs, and it is frequently of interest to know precisely how many discs are on a spindle at a given stage.

Since the stacked discs have relatively well-defined edge geometries, and since the stacking rings generally give rise to small gaps between discs, simple scanners that view the edge profile of a stack ought to be able to make a precise count. The difficulty comes when one realizes that in practice the edge geometries are not very well defined, and that in many cases the gaps between discs are either tiny or essentially nonexistent.

Disc edge geometry can be a problem because depending on the fabricator, and even on the particular press within a process, disc edges can be beveled, tapered, or otherwise different from the simple edge of a cylinder. The situation is further

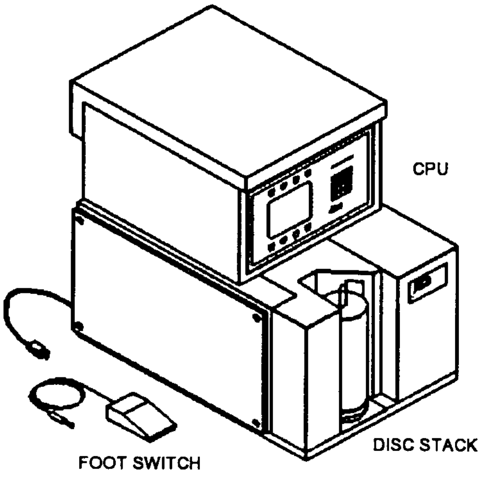


Figure 6: Compact disc counter

complicated by the fact that spin coaters often leave lacquer drips along the edges, thereby making the achievement of reliable optical signals difficult.

Gaps between the discs are not always obvious either, because of warp or because the stacking rings are very small.

Even with these complicating factors, it is possible to design a device that automatically counts discs with high accuracy and reliability. The A.I.D. system can count discs stacked to a height of 295 mm (approximately 200 discs), and completes the count about 5 seconds after the unit is activated by a foot switch. The optics involve the use of a simple halogen light source and a 2,048 pixel linear array camera - thus, each pixel sees a 0.15 mm field of view, so that nominal disc thicknesses correspond to about 8 pixels. Figure 6 shows a drawing of the unit.

The illuminating head first scans the stack to establish an automatic baseline that depends on the optical signal available, and then makes a second pass during which the actual count is made. Each of the two scans takes about 2.5 seconds to complete.

A unique set of software algorithms is responsible for sorting out the aforementioned imperfections and variations in disc edge profile, and tests show that errors in disc count occur in less than 0.1% of the trials. When a miscount does occur, there is usually evidence of a problem during the two scans, and a repeat count is usually sufficient to get the right number.

To date, the disc counter system has been configured and tested for only a few of the many geometries that exist in the industry, and it is not unlikely that an edge geometry exists that could prove difficult for the device.

EMERGING APPLICATIONS

As mentioned in the introduction, new optical disc applications are emerging, particularly in the video disc and data storage media technologies. A.I.D. has been active in these areas, and has either introduced or is evaluating inspection products for a variety of new applications. The baseline optical "engine" for A.I.D. inspection systems is the telecentric optical system discussed in some detail in Section 2.1, but the illumination source, linear array camera, and number of optical channels varies depending on the requirements at hand. Similarly, the microprocessor configuration, application software, and details of the inspection process can also vary from application to application. Specifics are given in the following sections.

300 mm Video Disc Inspection

A.I.D. recently introduced its 300 mm video disc inspection system, which in concept resembles the audio disc system and a 200 mm video disc system that was introduced in 1989. The most obvious difference between the audio and 300 mm video disc is the sheer size of the latter, which presents unique problems for warp inspection. In addition, although 300 mm discs are fabricated as single sided halves, the final product usually consists of two of these halves bonded together to form a double-sided disc. Single-sided halves are easily inspected for pin holes, but in bonded discs it is not possible to use the overhead light for pin hole detection.

Other differences are also apparent: many fabricators use PMMA as the substrate for video discs, and this material is characterized by low birefringence, so that inspection for this property may not be necessary. At the same time, difficulties in metallizing PMMA have been reported, and it is possible that one manifestation may be the presence of pin holes in the metal layer. Also, it is not clear at present that polycarbonate will not also be a material of choice, and if it is, stress-induced birefringence will be no less important than it is in audio discs.

Given the relative infancy of the video disc industry, and the virtual nonexistence of automated inspection, it is not at all clear at present what defect types and sizes will ultimately have to be detected, or what realistic acceptance criteria might be, beyond making some educated guesses. Thus, it can readily be anticipated that software algorithms will need to be refined, and that in all probability both inspection times and resolutions will have to improve as experience is gained. Initially, however, most fabricators agree that the ability to detect

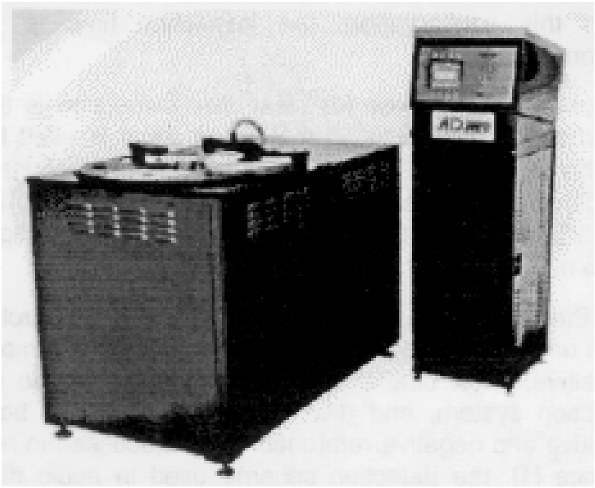


Figure 7: 300 mm video disc system

50 µ defects should be adequate, and that an inspection time of 15 seconds is acceptable. Most fabricators also agree, however, that longer term resolutions will probably have to improve to the 20 µ range, and that inspection times approaching 3 seconds may be necessary.

The A.I.D. video disc inspection system employs the same basic telecentric optical systems that are used for audio disc inspection (see Fig. 1), but in this case the field of view is about 100 mm rather than the 40 mm that characterizes audio systems. Both the defect and birefringence channels use 2,048 pixel linear array cameras, so that the pixel-to-pixel spacing is 46 µ. The disc is scanned 18,000 times during the course of a rotation, and this results in a scan-to-scan spacing of 51 µ at the outer edge of the disc, and a spacing of 20 µ near the hub. The scan time for a disc is 14.4 seconds when both cameras are active, but if birefringence scanning is not desired, the birefringence camera can be deactivated, in which case the scan time reduces to 7.2 seconds.

Figure 7 shows the basic inspection system, and it will be noted that a three-station carousel arrangement is employed. The reason for this approach is that defect and warp inspection are carried out at different stations: given the large size of video discs, warp is likely to be more severe than in the smaller audio discs. This fact can make defect inspection difficult unless a special mounting arrangement is used to hold the region of the disc over the inspection cameras as flat as possible. For this purpose, specially designed rollers position the outer edges of the disc level with the plane of the spindle, which clamps the disc in place at the hub. Warp measurement, on the other hand, requires that the disc be unconstrained at the edge, and the mounting arrangement at the other station therefore consists of a center spindle to clamp the disc but no such edge positioning devices. The third station on the carousel is for loading and unloading the discs, either manually or by an automatic handler. In operation, a disc is loaded and then automatically indexed to the warp inspection station by the carousel. After this, it is again indexed to the main inspection system, while the next disc is rotated into the warp station. Finally, the disc is rotated back to the first station for unloading.

Warp measurements are based on a beam deflection principle in which an incident beam of light is reflected from the undersurface of the disc in the warp station and is detected by a position sensitive device capable of detecting deflections in both the radial and tangential directions. This means that the system can independently measure both radial and tangential components of warp, rather than just an overall effective warp. If D_t is the total effective beam deflection angle, D_t the tangential deflection, and D_r the radial deflection, the three quantities are related in the limit of small angles by

$$D_T = \sqrt{D_t^2 + D_r^2}$$

The optical head of the warp gauge can be manually placed at any radial position on the disc. As the disc is rotated, the device continuously reads the deflections on the circumference corresponding to this radius, and saves the maximum detected values of both the radial and tangential deflections, which need not occur at the same point on the disc. This information is then transmitted to the main CPU, where it is compared with the two user-specified acceptance limits. No accept or reject action is taken until the completion of the defect inspection, since the disc must continue on to the defect inspection station regardless of the warp result.

Defect inspection is quite similar to that carried out on audio discs, and at present many of the same defects are detected and reported. If the birefringence camera is not in use, global birefringence and the local birefringence contributions to track flaws are not included in the inspection.

The system has been designed to accommodate both disc halves and bonded whole discs without the need for any particular set up procedures. In the case of bonded discs, of course, pin holes cannot be distinguished from other defect types, so the overhead light source is not needed.

MO and WORM Discs

Systems for the inspection of “write once, read many” (WORM) and magneto optical (MO) discs are in development at A.I.D., and two prototypes are presently being tested

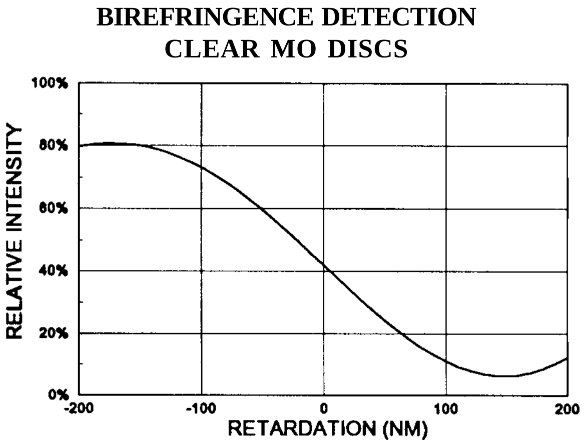


Figure 8: MO disc birefringence detection

in plant environments. As is the case with 300 mm video discs, both technologies are relatively new so that the requirements for automated inspection are not yet well-defined. A few general observations can be made, however.

First of all, both disc types involve the use of relatively high value coatings, so there is motivation to insure that these coatings are not wasted on defective substrates. This fact makes inspection of transparent substrates more important than it is for audio and video discs.

Second, the coatings on WORM and MO discs are more complex than the simple aluminum layers on audio and video discs, and do not have the same optical properties as aluminum. It is therefore likely that the inspection of coated discs will require illumination sources whose spectral properties are substantially different from the simple white light sources used for audio and video discs.

Finally, while no specific resolution requirements have been established, it is likely that it will be necessary to detect defects at least as small as 20 µ in the near term, and quite possibly, defects as small as 10 µ in the longer term. Furthermore, inspection times between 5 and 10 seconds may be adequate for the present, but these are likely to shorten significantly as production processes mature.

For clear disc inspection, the first prototype system developed at A.I.D. employs a 2,048 pixel defect camera in combination with a 512 pixel birefringence camera. The pixel spacing for localized birefringence is therefore identical to that for the audio disc system, but the corresponding value for defects is 20 µ. When the number of scans is set for 18,000, the scan spacing is 21 µ at the outer edge of the disc and 7 µ near the hub. With this configuration, the inspection time is 11 seconds.

The main light source for clear disc inspection is the overhead lamp, which on metallized discs is used for pin hole discrimination. Also, the birefringence channel employs an overhead reflective surface to replace the metallization layer that normally back reflects the light from metallized discs.

Another change that was incorporated into this prototype unit is a retarder system that makes the unit more sensitive to low birefringence levels than the audio inspection system, and also enables it to detect both positive and negative retardation. As discussed in reference [1], the detection scheme used in audio disc systems is relatively insensitive to retardation values and changes in the ± 50 nm range, but can measure retardation to within ± 10 nm near the usual acceptance limit of 100 nm. In MO discs, it is sometimes of interest to detect retardation values and changes that are in the ± 20 nm range, and this can be accomplished with a system that has a detection characteristic like that shown in Figure 8. This is the actual calibration curve for the prototype clear disc system, and it is apparent that the response is reasonably linear over the ± 100 nm range. The sensitivity to small changes can be improved simply by increasing the slope of the curve, which is accomplished by adjusting amplifier gain. However, the total dynamic range for detection decreases in inverse proportion to the slope.

The second prototype system developed is similar to the audio disc system in that 1,024 and 512 pixel cameras are used for the two optical channels, thereby giving identical resolution, but the illumination source was changed from broad band, white light centered at 630 nm to narrow band, infrared light centered at 780 nm. This change has actually been accomplished using both a laser source and a heavily filtered white light source. The two are essentially equivalent approaches, but the laser source offers more convenient packaging and narrow banding than the white light source. The trade-off is that the laser also introduces optical coherence problems, which must be overcome for reliable use in an inspection system. This is not all that difficult to do, and it is likely that future systems requiring infrared illumination will employ laser devices.

FUTURE DIRECTIONS

It has already been noted several times that as experience is gained with the production of video, MO, and WORM discs, requirements for both faster inspection times and improved resolution are likely to arise.

Similarly, MO and WORM discs are both likely to require the use of narrow band, infrared sources which may in addition have to be tunable. Fortunately, all of these requirements appear to be well within the current state of the art of microprocessor and optical technologies.

Higher Resolution Systems

Higher resolution requirements can be met either by employing single cameras with more pixels to cover a given field of view, or by employing multiple cameras to view this same area. The scan-to-scan spacing must also be reduced accordingly by adjusting the stepper motor. The single camera approach is perhaps the simpler, since no additional optical alignment or adjustment is needed. As an example of this approach, a 4,096 pixel linear array camera will result in a pixel-to-pixel spacing of about 20 µ for a 300 mm video disc, and a spacing of 10 µ for an MO or WORM disc. Such a camera would satisfy requirements that are likely to arise in both areas.

The multiple camera approach is identical in concept, but more difficult to implement in practice because it is likely to involve very precise alignment, overlapping fields of view, and software algorithms that avoid double counting of defects within the region of overlap.

Both approaches require additional illumination intensity, since the pixel sizes are smaller. This is not a trivial problem, but sources are available which, with suitable engineering, can meet the requirements.

Faster inspection systems

Improved resolution and faster inspection times are competing requirements, since data rates increase inversely as the effective area viewed by a “scan-pixel” element. Thus, for example, if the number of pixels covering a field of view is doubled to cut the pixel-to-pixel spacing in half, and if the number of scans is also doubled for the same reason, four times as much data must be processed.

The most straightforward approach to overcoming the longer inspection times that would otherwise result is to use faster camera readout and data processing speeds. Indeed, this approach has already been used in developing the high-speed audio disc system (see section 3.1). An approach that is likely to yield more dramatic results, however, and which may also be easier to implement, is parallel processing. Here, the pixels from different cameras, or even within the same camera, are fed to multiple processors which can then do the necessary reductions simultaneously. Upon finishing this processing, the output is then combined for comparison with acceptance criteria.

As an example of the parallel processing approach, suppose that double the present resolution is required for a particular process. Since there is a four-fold increase in data rate, four parallel processing channels are needed to accomplish the inspection with no increase in time. If the process also requires a four-fold reduction in inspection time, either faster processor speeds or additional parallel processing paths can be employed.

Some 4,096 pixel cameras are ideal for parallel processing applications, since they are tapped in such a way as to allow sections of pixels to be directed to different processors. These cameras are presently under investigation at A.I.D.

Improved Defect Characterization

Depending on the defect classifications of interest to disc fabricators, it will probably be necessary to refine the software algorithms that are presently in use in the audio disc area. In addition, it may prove necessary to retain more information about the defect than the few threshold crossings that are now used (see Section 2.2). This may require, for example, the use of additional thresholds, the processing of gray scale information, or both. In either case the requirements on the microprocessor will increase, and must be dealt with.

An example of improved defect characterization that might be met with software development is the differentiation between a bubble and a black speck. Both of these are now reported only as T2 threshold crossings, and so the inspection system cannot distinguish between them. Suppose, however, that one of these has associated with it a local birefringence field that extends over a long distance, while the other has a birefringence field that is of much shorter range. If the software can correlate the presence of T2 crossings with the spatial extent of the birefringence field, it may well be possible to distinguish between the two defects. While such refinements are likely to be software intensive, improved hardware might also be needed to prevent increases in inspection time.

SOME LIMITATIONS

To date discussions of the possible need for improved resolution have not seriously extended below 10 µ. It is possible, however, that even better resolutions will be required in the future. While additional improvements are by no means out of the question, it must be remembered that optical systems are ultimately wavelength limited because of diffraction

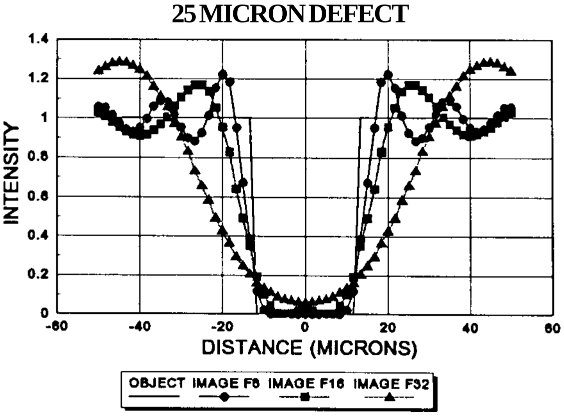


Figure 9: Diffraction distortion of defect

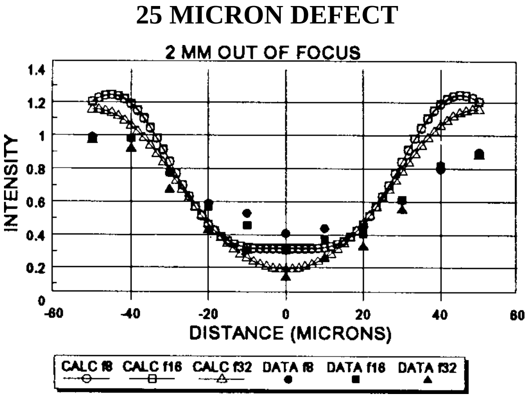


Figure 10: Total distortion of defect

effects. If white light is used, the wavelength in question is about 630 nm. For infrared illumination sources, the wavelength will be slightly higher - about 780 nm.

Laboratory tests at a 20 µ pixel spacing indicate that, while there is no difficulty detecting a comparably sized defect, diffraction effects become noticeable at higher camera f-stop settings. The "defect" investigated was a 25 µ wide line which causes no refraction or scattering and therefore behaves like a simple light blocker whose optical contrast is 100%. Figure 9 plots the profile of the line as it appears in the object and image planes, for three different f-stops. Figure 10 shows calculations and data for the same defect when the image is 2 mm out of focus and the signal has been distorted by diffraction, averaging over the pixel dimension, and band width limitations of the electronic detection system. It is interesting to note that although the apparent width of the detected signal is substantially greater than 25 µ, the optical contrast is still more than sufficient to allow easy detection by the thresholding systems used in A.I.D. inspection systems.

Although distortion by integration over the pixels and by filtering in the amplifier can be controlled within limits, Figure 9 makes it clear that diffraction is already beginning to limit the system response at 25 µ. Some of this distortion can be reduced by opening the camera lens to a lower f-stop value, but for most defects optical contrast will suffer as a result. Diffraction limitations can be expected to become even more pronounced for smaller defects, in which case averaging over pixel size and filtering by the amplifiers will become relatively less important. Thus, the limitation to defect detection takes on a more fundamental character, which is closely related to the use of conventional optical techniques.

It will be noted that in the results of Figures 9 and 10, sampling by pixels that are 20 µ in dimension does not meet the frequently-invoked Nyquist criterion that the spatial sampling frequency be at least twice the maximum spatial frequency contained in the signal. Thus, the signal shape cannot be reproduced faithfully, but given the thresholding techniques used by A.I.D. inspection systems, this is more a limitation to proper sizing of the defect than to detecting it. For larger defects, the Nyquist criterion is generally met, so that sizing becomes correspondingly more accurate.

As the sizes of defects which must be detected become smaller, it is unlikely that commercially available CCD devices will have pixel sizes that can meet the Nyquist sampling condition. Thus, some distortion of the defect shape will be unavoidable, even if diffraction were not a limitation.

REFERENCES

1 D. T. Sturgill, *Direct Imaging for Verification of CD Quality*, Proceedings of the 31st Annual Technical Conference, Society of Vacuum Coaters, p. 155 (1988)

2 G. R. Mather, Jr. and A. Harmala, *Automatic Inspection of Compact Discs*, Proceedings of the 33rd Annual Technical Conference, Society of Vacuum Coaters, p. 64 (1990)