Digital Radiography in Industry: Digital Detector Arrays in Radiographic Testing
by Brad Kraai

Introduction

Digital detector array (DDA) systems within industrial radiography are becoming very common in high performance, critical margin of safety, and endurance test article inspections. Investment castings, thermal joints, and a wide variety of other test articles are being routinely inspected, with improved probability of detection (POD), and much faster throughput than conventional film systems—with high levels of user satisfaction. Potential users within the industrial X-ray imaging community continue to recognize these values and exploit this new technology for potential applications, but to do so, a basic understanding of DDA systems and application is a necessary foundation. Smooth implementation of this novel technology can be challenging, and consultation should be considered from an outside, unbiased, reputable organization.

There are several integrators, or vendors, that are widely recognized as providers of DDA systems development, installation, and service—each having its own merits and specialties.

Definitions

Per ASTM E 2736, Standard Guide for Digital Detector Array Radiology, a digital detector array is defined as: “an electronic device that converts ionizing or penetrating radiation into a discrete array of analog signals which are subsequently digitized and transferred to a computer for display as a digital image corresponding to the radiation energy pattern imparted upon the input region of the device. The conversion of the ionizing or penetrating radiation into an electronic signal may transpire by first converting the ionizing or penetrating radiation into visible light through the use of a scintillating material” (ASTM, 2010a). While DDAs can be used for real-time or radioscopic techniques, most applications for critical test articles employ static imaging and evaluation. Figure 1 provides a simplified diagram of a DDA.
The most popular types of DDAs in use contain an initial and indirect conversion layer (or scintillator)—typically either gadolinium oxysulfide terbium doped, or cesium iodide thallium doped—that converts an X-ray signal to visible light or luminescence. This luminescence then enters the amorphous silicon ($\alpha$Si) thin film transistor diode array (discrete pixel locations), whereby the light is converted to an electronic voltage (bias change) at each pixel, which is subsequently “read out” of the array in channels and groups during X-ray exposure. This electronic information is amplified and then digitized, typically through several analog-to-digital converters, synchronized, and sent to the frame buffer within the image processor and system software.

Gray values for each pixel’s digital (binary) value are then assigned by a lookup table, and a corresponding pixel matrix that represents X-ray attenuation from the initial image acquisition is generated and considered as the raw or full fidelity image file. This image file also contains meta-data, or image tags of process information as configured by the system integrator. The raw or full fidelity image is saved unaltered for critical applications. Raw image file size primarily depends on the resolution, or pixel pitch, and input region (or array size) of the DDA, as well as its bit depth.

As one can see, DDAs are quite sophisticated electronic conversion devices. Yet, they can provide simplicity to the radiographic imaging process, as consistency and reliability are often the result of a properly engineered, tuned, and applied DDA system.

**Applications**

For the purpose of application validation, a potential user must evaluate “representative quality indicators,” or, more simply stated, potential test articles with known conditions or defects (of a minimum size and all types likely to be encountered) for any DDA system under consideration. Quite often, DDA systems are designed and built around a target application or family: the potential test articles to be inspected with the DDA system will all be related—similar in material type and material thickness, subject contrast range, and inspection standard criteria. It is the responsibility of the potential user, not the integrator or vendor, to ensure that DDA system performance metrics are met for a given target application. Obviously, DDA systems are a considerable capital expenditure, so once the system is designed, built, and installed, it must meet the requirements—resolve the defects reliably—as intended. This cannot be overemphasized. Film images are commonly used as the baseline or referee for a correlation study with the DDA imaging techniques, and will often be required for process approval.

High levels of automation are possible and often used with DDAs. Imaging, from one acquisition to the next, can be mere seconds, depending on the type of DDA and acquisition settings, technique, and level of automation. Fully articulating and programmable robotics within custom-built radiation enclosures are becoming quite common in turbine blade inspection; a single blade can be imaged with several views in less than a minute. Other automation tactics may include external ingress of test articles into the enclosure by conveyors, or manual loading of numerous parts in fixtures or platens. DDA systems with turntables for the test article and a C-arm—with the X-ray tube on one end and DDA on the other—are commonly used for larger test articles. Other sophisticated systems have incorporated two robots: one for the X-ray tube and the other for the DDA, while the test article remains stationary. System integrators can be creative, and depending on the target application, will often readily collaborate with the potential user to design and incorporate optimized article handling and imaging for the intended application.

It must be realized that DDAs are in fact a consumable, and will eventually require replacement due to performance issues or degradation. They will and do fail (unpredictably, in most cases) over time. The cumulative effects of radiation exposure and thermal variations within the device produce effects that may range...
from image quality degradation all the way to failure. There are no guarantees of a DDA’s usable duration. Inadvertent or unintentional exposure to the DDA should be avoided. Recent developments in hardened electronics have increased DDA resistance to exposure effects. Shielding of the electronics around the periphery of the DDA must be provided by the integrator, and should be analyzed by the DDA manufacturer for warranty viability. Moreover, users of DDA systems must contemplate detector failure or sub-par imaging contingency and warranty when negotiating procurement.

As mentioned previously, the DDA and its supportive software are very complex. This DDA system complexity can be very intimidating, so a word of advice: complexity of the entire DDA system should be held to a minimum—configurations should be limited to fit the needs of the user. During DDA system design and development, it is vital that the potential user recognize excessive complexity for what it can be—and often is—the enemy of execution. Careful analysis of all DDA system features and their intricacy may reveal unwanted or unwarranted complication.

Capabilities

While DDAs are challenged for image spatial resolution, due to the finite resolutions (discrete pixel dimensions or “pixel pitch”) currently available, the contrast sensitivity for these devices is remarkable—provided noise is controlled.

Due to inherent DDA resolution, geometric magnification ($M$) techniques are often employed, which amplify discontinuity size and enhance POD via a higher number of pixels under the potential discontinuity or feature within the test article. It is a relatively simple matter to calculate for a specific number of pixels under a known dimension at geometric magnification, and quite often, the calculation is applied to determine pixel density within an essential image quality indicator (IQI) hole dimension. The minimum recommendation is three pixels, so by using the basic spatial resolution ($SR_b$) of the DDA, and the specified IQI hole size ($d$), minimum geometric magnification can be calculated by the following equation (Figure 2).

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M_{\text{min}} = 4.25 \times \frac{SR_b}{d}
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For example, if $SR_b = 215 \ \mu m$ (0.008 in.) and $d = 508 \ \mu m$ (0.020 in.), $M_{\text{min}} = 1.7987X$ (1.8X). Obviously, as the $SR_b$ value decreases (for higher resolution DDAs having a finer pixel pitch), the $M_{\text{min}}$ required to achieve the recommended $3 \times 3$ pixel matrix in the IQI hole decreases in turn. Higher $M$ factors increase pixel density for a specific dimension within the image, thereby promoting higher POD. Higher $M$ factors applied within techniques will decrease the image field of view, resulting in decreased throughput for larger test articles as compared to the DDA input region.

Another primary consideration for any geometrically magnified technique is image unsharpness ($U_{\text{img}}$), wherein a reduced effective focal spot size (EFSS) is often necessary at higher magnifications. $U_{\text{img}}$ calculations take into account the geometric unsharpness ($U_g$) of the technique, (where $[M – 1] \times \text{EFSS} = U_g$), the geometric magnification factor ($M = \text{source-to-detector distance} / \text{source-to-object distance}$), and the $SR_b$ of the DDA. $U_{\text{img}}$ can also be evaluated by imaging, at the source side of the area of interest, a unique IQI—the duplex wire gage (Figure 3)—to determine which specific wire pairs merge within the acquired image: $U_{\text{img}}$ then being regarded as that specific wire diameter and its adjacent space combined. $U_{\text{img}}$ and geometric magnification are both important technique parameters that must be well understood and evaluated prior to DDA system build.

Several techniques exist for minimizing noise: acquired image noise can never
be fully eliminated, and is composed of signal and system noise. Common noise reduction tactics include frame averaging, DDA calibration, X-ray beam filtration, X-ray beam collimation, and exposure optimization. The averaging of frames basically provides better statistics for the raw image data, by adding the pixel signal value for each individual pixel through all frames captured, dividing by the number of frames, and assigning the averaged value to that pixel for the raw image. Averaging more frames impacts throughput, increases dose to the DDA, and typically only presents improved statistics at a threshold. DDA calibrations, or normalizing, are a necessary function of the DDA imaging process. Most users apply calibration techniques for DDA offset and gain per the integrator or vendor’s recommendation. Offset is basically dark or inherent noise within the DDA, and gain is inconsistencies in pixel responses (amplitude or gain) during exposure. Without normalization, any DDA would basically be unusable for an application. It is extremely important that the user establish DDA normalization protocol and evaluate its efficacy. X-ray beam filtration is often employed, thereby attenuating certain portions of the soft radiation spectrum, which in turn reduces noise and improves signal-to-noise ratio (SNR). Experimentation is key, and SNR can be evaluated during system validation and technique development. Applying filtration also reduces dose to the DDA, which may increase its lifespan. Collimation, or restricting the X-ray beam to only illuminate the input region of the DDA, will also lower signal noise and reduce dose to the DDA’s electronics. Besides fixed collimators, there are also programmable X-ray beam shuttering mechanisms that can be completely closed (for X-ray system warm-up) or opened/closed, as appropriate, for the imaging technique. Proper exposure ensures optimized signal capture within the DDA, and a translation to low contrast sensitivity. Within any signal amplification, the law of Poisson exists, where noise will increase by the square root of the variable signal increase (exposure). That being said, higher exposure or signal provides higher SNR, albeit with an increase in exposure time or image acquisition, and effectively a higher dose to the DDA. High SNR results in extremely low contrast sensitivity capability for DDA techniques: quite often well below 0.5%, particularly for thinner areas of interest within test articles. This high SNR also contributes to high contrast-to-noise ratio (CNR), as measured within an image of a conventional IQI. Figure 4 illustrates a CNR measurement on a 0.05 IQI, 127 µm (0.005 in.) T, on a 1.27 mm (0.05 in.) thick base material. As important technique attributes, SNR and CNR measurement can be accomplished with specific tools within most imaging software. High CNR values are not possible without high SNR values, and these two metrics can be used to validate one another—provided measurements are consistent and controlled.

The available DDAs are normally 14-bit (\(2^{14}\)) or 16-bit (\(2^{16}\)), 0 to 16 383 or 0 to 65 535 possible pixel values, respectively: very long scale as compared to the limited scale of film—that is, 1.50 to 4.00 H&D (Hurter and Driffield), or -250 usable radiographic optical densities. The usable range of the DDA will always be less than the full scale or bit depth, but is still significant. This long scale enables the very low contrast sensitivity mentioned previously—provided noise is controlled. The long scale also provides adequate image quality through a wider thickness range in one exposure. Another advantage of DDAs is this very high dynamic range as compared to short scale imagers, mainly film.

As can be clearly seen, there are multiple variables that must be evaluated and correlated during DDA system consideration and design. Resolution and contrast performance for any radiographic imaging system are the primary objectives, and the requirements for the inspection application must be recognized and understood. The characterizations of performance within any DDA system are various, but can be boiled down to system SR\(_{\text{p}}\), allowable or required geometric magnification, \(U_{\text{img}}\) and contrast sensitivity through the material type and thickness range to be inspected. Many other considerations exist, more or less depending on the target application, that are beyond the scope of this article. Realistically, at the beginning, middle, and end of the day, the required performance of the DDA system is just this: to consistently and reliably detect and accurately portray substandard defects for the selected application and its technique.

**Process Controls**

Any DDA system’s performance must be monitored for instability and degradation. Most users apply a duplex plate phantom (DPP) and specialized software to enable consistency within the measurements required for stability and performance. The DPP (Figure 5) must be of the same material group as the inspection application, with a thin and thick section closely matching the thinnest and thickest sections of the test article(s).
uncorrectable bad pixels—referred to as cluster kernel pixels (CKPs)—may increase the risk of missed defects to the point that DDA replacement is necessary. Avoiding imaging within the area of the DDA that contains CKPs is also an acceptable practice but normally involves reprogramming for test article positioning and possible reductions in usable field of view. DDA bad pixel and CKP considerations are all about management, through mapping the DDA and evaluating the bad pixel distribution list, and most importantly the presence of CKPs, at predetermined intervals or as necessary. The DDA system user or agent should evaluate the bad pixel map and distribution list of the purchased DDA upon system buyoff and also evaluate the DDA for bad pixels upon system delivery.

Ongoing production image quality is most often verified by the use of a qualifier image, or image capture of a specific quality indicator (conventional IQIs or other) at a prescribed frequency, due to the automated inspection environment. It is not necessary, nor practical in most cases, to include an IQI within each image acquisition. Qualifier images are acquired and evaluated at a prescribed frequency, usually at a minimum of once per shift as determined by the user and approved by the end user or customer, and these images qualify all acquired images to the previous qualifier. If the qualifier does not present the required level of image quality, all previous images to the last viable qualifier are then considered invalid. The user must assess the reprocessing risk and possible burden associated with qualifier frequency and application.

Not unlike any nondestructive testing process, practices for process controls must demonstrate system repeatability and reliability, providing confidence and value for the user and customer.

### Image Attributes and Evaluation

Any digital image is a matrix of pixels, each pixel having a relative value and X, Y coordinate address (where X = column position and Y = row position)—pixels are also defined as the smallest component of the image that may be altered. The acquired DDA image, being of very long scale, requires image processing or alteration across the matrix, to render discontinuity or feature visibility with human vision. There are many different processing techniques than can be applied: spatial filters, window/level adjustments, and electronic magnification (zoom) being most often utilized. Any image processing techniques must be validated, documented, and controlled—it could be said that there is a viewing technique as well as an imaging technique due to the variety of tools at the technician’s disposal. Image discontinuities, features, and attributes can be analyzed or quantified with various tools contained within most software platforms. Line or area profiles, linear measurements, regions of interest for SNR/CNR measurements or local image processing, histograms, and other implements are available for these purposes. Annotation tools are used to identify and characterize image indications, and can either be saved as an overlay, or placed permanently within the image provided they do not mask or obscure an area of interest. Training and experience, and scripted work instructions, complement the accuracy and consistency of image evaluation activities.
The digital image display should be a high performance, medium to high resolution, liquid crystal display (LCD) or LCD/liquid-emitting diode type. Typically, medical grade monochrome displays are incorporated into the DDA system viewing workstation. High luminance (brightness), as measured in candelas per square meter (cd/m²) at 100% digital driving level (full white) is warranted, to promote high visible and quantified contrast. A video test pattern, most often the Society of Motion Picture and Television Engineers’ SMPTE RP-133 or an approved variant, is presented and evaluated for spatial precision, visible contrast, and measured contrast performance of the display (SMPTE, 1999).

The digital image viewing ambient environment requirements are basically identical to those of radiographic film viewing, but the evaluation of soft copy images has proven to be much more consistent, ergonomic and less rigorous than hard copy image handling and viewing, resulting in higher levels of technician confidence, performance, and contentment (Figure 6).

Personnel Qualification

Potential users of DDA systems also have the challenge of fully qualifying technicians and Level 3s for this new imaging process—the beginning of which is the revision of the user’s written practice for qualification and certification of DDA personnel. Most users are making the transition from film-based radiography, so initially, the radiographic testing (RT) Level 3 must be considered for DDA Level 3. Formal training is required, and any experience gained toward qualification includes, but may not be limited to, DDA system design and application studies, vendor demonstrations, and technical conferences. Experience should be accumulated under supervision or guidance of an examiner, instructor, or outside agency. RT Level 2 promotion to DDA Level 2 begins with 40 h of formal training and the required hours of on-the-job training/experience (OJT/OJE). The formal training should be administered by an experienced, requirement and application savvy instructor, and should occur prior to, or in conjunction with, OJT or OJE. The OJT/OJE should be well organized and delivered under structured planning and documentation. Technicians can then be fully qualified by examinations as required by the employer’s written practice and subsequently certified. An audition period or secondary review of a newly certified DDA Level 2’s image evaluation is often appropriate, and may be required by the end user or customer.

Starting from scratch would require a similar regimen as film radiographer qualification and certification for the DDA Level 2.

Conclusion

Increased radiographic inspection throughput, higher POD and disposition accuracy, reduction in consumable costs, and the anticipated solid return on investments for DDA system users can be realized with proper understanding, planning, and implementation (Figure 7). Potential users must decide if outside assistance is necessary—at the beginning of the DDA system selection process—instead of during or after. This proactive approach can facilitate the process efficiency, investment returns, and user satisfaction that DDA systems are capable of providing.

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REFERENCES


AUTHOR

Brad Kraai: X-Ray Industries, Inc., an Applus RTD Co., NDT Training, Consulting & Services Group; e-mail brad.kraai@xrayindustries.com.