DIGITAL MEASURING BORESCOPE SYSTEM

Gene McGarry

Olympus America Inc.
Endoscope Division
Industrial Products Group
2 Corporate Center Drive
Melville, New York 11747

BACKGROUND

Past attempts at endoscopic measurement have borne many interesting theories yet yielded only limited degrees of success. Most importantly, however, were the users' concerns for reliability and repeatability as compared to traditional methods of non-destructive test or, in the worst case, the undesirable resolve to top-case a turbine. The user's decision to proceed with a major maintenance expenditure or perhaps remove a power plant from service has been, as a rule, based largely on subjective interpretations of what is viewed and measured through a borescope.

There are many factors that influence one's perception of an object when it is viewed through a borescope. Some are inherent to a system's optical configuration while others are based on the individual's personal interpretation. Then ideal measurement system will maximize optical resolution and minimize subjectivity while making the inspector's task as straightforward as possible.

IMAGE CAPTURE

The ability to perform in-situ measurement is based on the resolution of the video imaging system, a function of the sum of the system components used to capture and display it. Image capture is accomplished via high resolution CCD cameras and borescopic objective lenses. These cameras usually contain up to 400,000 pixels or image gathering elements. Intuitively, the more information gathering elements - the higher the resolution. The rigid borescope lens configuration (as compared to smaller CCD's and coherent fiber optic bundles) maximizes the information delivered to the CCD camera.

A measure of performance of an endoscopic measuring system must consider the above. For industrial applications, the more common, high resolution platform for remote image capture is the eight millimeter diameter rigid borescope. It is designed about a lens imaging system that delivers fiber optic illumination to the internal worksite. Special lens coatings produce a bright image that is projected onto a 1/2" CCD, closed circuit television (CCTV) camera. Given the appropriate display, the viewer will observe approximately 470 TV lines (horizontal) of imaging system resolution. The scope's small diameter, variable direction of view, and rigid insertion section design suit it well mechanically for the majority of common industrial applications.
The typical industrial borescope is designed with a 50° to 60° field of view (FOV) that approximates the field coverage of the human eye. This is an ergonomic design that facilitates general observation and provides the user with a broad perspective. Because it employs a lens system, the borescope’s resolution is high. When using this standard fixed FOV scope, observed detail and magnification can only be increased by moving the objective lens (distal tip of the scope) closer to the target (see Figure 1).

This relationship remains valid and useful until the working distance from the target to the objective lens is reduced to “Near Point Focus”, more commonly referred to as the minimum focal distance. From this point, as the target moves closer to the scope the image will move out of the focal range and become unusable. Given that the vast majority of in-situ measurement applications do not provide enough space to reposition the scope, an alternative method is chosen.

This option is based on a fundamental borescope design that includes a “zoom” ocular or objective. This type of system provides the user with a variable FOV and greater magnification. In small endoscopic packages, it is cost and performance prohibitive to incorporate the necessary mechanics for a zoom objective. Although the back end, or ocular zoom, does provide a significant improvement in magnification it makes extremely inefficient use of available light. For example, if an image is zoomed to 3X magnification it will only retain about 1/3 of the scene illumination. This is because the objective system’s aperture remains constant while the effective imaging area is reduced by 2/3 excluding the balance of available light incident on the scene.

For borescopic applications, the most efficient method for increasing magnification and resolution is to reduce the fixed, objective FOV. Magnification increases exponentially as the FOV is decreased (see Figure 2). As the effective target area becomes smaller - lens diameter remaining constant - the image is captured in much greater detail sending more information to the camera. The aperture design is optimized to make efficient use of available light for this objective’s specific field coverage.

Most important to the DMBS, however, is the controlled depth of field (DOF) achieved from the specific aperture design. The system is designed with a shallow DOF (see Figure 3).

Inspection targets are viewed in focus as far as infinity yet a range of specific target distances is precisely defined. Relative position of these distances is recognized by an optical encoder which is linked electronically to the focusing barrel of the borescope.

At comparatively large distances, with respect to specific objective design, resolution of position is less precisely defined and a new, higher magnification FOV must be incorporated to accomplish the same. As detailed later, the DMBS exploits this imaging characteristic by processing those known focal distances through the video analyzer in determination of target distances and actual defect size.

**IMAGE DISPLAY**

When performing video measurement the display quality is as important as that of the image capturing system. Like the image capture device, a high resolution display contains a larger number of pixels, or image elements, than a lower resolution display. To maximize the resolution of the video measurement cursor position, the display must minimize the contribution toward measurement of each independent cursor move (each move between adjacent pixels on a display). The smaller each incremental cursor move, the greater the measurement resolution and accuracy.
Figure 1 - The relationship between “Working Distance” and “Magnification”.

Figure 2 - The relationship between “Field of View” and “Magnification”.
The significance of a high magnification objective imaging system in now clear. If an object is under low magnification it will appear relatively small on a display and each incremental video cursor move across that object (pixel to pixel) will translate into a large value (percentage of the object). If the converse is true - the magnification is high - the object will appear larger on the display and each incremental cursor move will now represent a proportionately smaller value, increasing the measurement resolution and accuracy.

![Figure 3 - A comparison of “depths of field”](image)

**VIDEO ANALYZER**

The video analyzer is a digital database used for computation and digital information storage. It contains a borescopic light source, a frame grabber to freeze and store digital image information, software to processes the digital image, software to communicate with the optical encoder on the borescope, software to execute the measurement calculation, and a video board which displays the resultant data. Additional image enhancement software programs are also resident for detailed image analysis. This instrument, compatible with a full range of video imaging devices, also serves as a platform for managing measurement data and generating relevant reports in the Windows operating environment.

**MEASUREMENT SYSTEM**

Having defined the individual components it is appropriate to address the measurement process. The steps are as follows (refer to Figure 4):
1. Insert the borescope to the target area and view the display to locate the indication. The swing prism feature of the scope enables the user to scan from 40° fore-oblique to 115° retrospective without repositioning the scope.

2. Select the **DMBS MEASUREMENT** ICON from the video analyzer menu.

3. Adjust the focusing barrel on the ocular of the scope to bring the desired target for measurement into a clear focus. As the barrel is rotated, the current focal point (which changes continuously) is displayed.

4. Select the remote **FREEZE** button on the scope body. The image is now frozen on the video analyzer. The optical encoder has relayed the target distance to the video analyzer.

5. Position the video cursors on the target per the menu prompts. The target distance, trigonometric details of the optical field (20° FOV), and cursor positions are processed by the analyzer in calculating the measurement which is displayed in user selectable units (millimeters or inches).

6. To store the image for further analysis or future reference select the remote **STORE** button on the body of the borescope.

7. To proceed with another measurement select the remote **FREEZE** button on the scope body. This will return the system to the live measurement mode.

---

**Figure 4 - The parameters for accurate measurement.**
A second mode for measurement applies the same concept in performing depth measurement. The procedure calls for measurement in the LIVE mode. Focus is set on a point (bottom of a pit) on the target. The operator selects the FREEZE button identifying a focal plane of reference. The focusing barrel is then rotated to focus on a second focal plane (a nearer edge of a pit). As the focus is adjusted, the encoder is transmitting the relative position of the two reference planes establishing a depth relationship between the two points while the delta in position and direction (+ or -) are continuously displayed.

The aforementioned measurement techniques rely on the accurate identification of the referenced "Target Working Distance". This calculation is based on an encoder resolution of 4000 counts to every $360^\circ$ of focus barrel rotation. The corresponding change in focal depth (change in target working distance) of the borescope is .05 inches for each degree of focus barrel rotation.

Stored images from either operation may be exported in unique image formats via a PC card slot, floppy disk, or magnetic optical disk. The operator also has the option to exercise telecommunications options via the internal or PC card modem. A text file has automatically been generated complete will be available with all relevant text and measurement data.

APPLICATIONS

This system for measurement has proven effective for application to common power plants. A condition of outward radial creep deflection on turbine buckets has created the strong potential for radial seal rub on stationary shrouds and bucket tip shroud cracking. Using the DMBS operators have been able to perform in-situ measurements to successfully verify the minimal allowable shroud engagement prescribed for continued operation of the turbine. Images and measurement data accumulated during the inspection are permanently stored and compared to future inspection data to assist in trend analysis and preventive maintenance.

In another application measurement has been recommended for analysis of fan blades. Adjacent blades in the fan of a turbine had been vibrating as a result repetitive engine cycling. Carboloy pads on the interfacing surfaces of the mid-span spacers, acting as dampeners, must maintain a minimum thickness for normal power plant operation. Accessing these pads via the "inlet plenum" and successfully quantifying remaining material thickness using the DMBS saved the operator a costly, unnecessary top case while precluding the possibility of a "catastrophic" failure.

Unmonitored cracks in the swirlers may lead to premature failure of the fuel nozzle. By accessing the combustion chamber via the ignitor port, measurement is performed at up to a seven inch working distance with little or no disassembly. The inspector is better able to monitor component wear.

These are some of the common proven applications for the DMBS. Many other applications using similar technology are currently under development.
SYSTEM ACCURACY

The DMBS is manufactured to the following accuracy standards:

<table>
<thead>
<tr>
<th>Working Distance (inches)</th>
<th>Feature Size (inches)</th>
<th>Maximum % Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>.4</td>
<td>.1</td>
<td>4</td>
</tr>
<tr>
<td>1</td>
<td>.2</td>
<td>4</td>
</tr>
<tr>
<td>2</td>
<td>.4</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>.6</td>
<td>5</td>
</tr>
<tr>
<td>4</td>
<td>.8</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>1.0</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>1.2</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>1.4</td>
<td>8</td>
</tr>
</tbody>
</table>

Four inspectors performed borescopic measurement of defects located in various stages of a high performance turbine. All measurements were taken in inches. A comparison of actual defect size vs. the inspectors’ results as measured with the DMBS is as follows:

<table>
<thead>
<tr>
<th>Actual Size</th>
<th>Inspector #1</th>
<th>Inspector #2</th>
<th>Inspector #3</th>
<th>Inspector #4</th>
</tr>
</thead>
<tbody>
<tr>
<td>.005</td>
<td>.004</td>
<td>.005</td>
<td>.006</td>
<td>.005</td>
</tr>
<tr>
<td>.023</td>
<td>.021</td>
<td>.025</td>
<td>.026</td>
<td>.021</td>
</tr>
<tr>
<td>.047</td>
<td>.050</td>
<td>.049</td>
<td>.048</td>
<td>.047</td>
</tr>
<tr>
<td>.046</td>
<td>.047</td>
<td>.047</td>
<td>.046</td>
<td>.048</td>
</tr>
</tbody>
</table>