Variable-resolution video moire error map system for inspection of continuously manufactured objects

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Variable Resolution Video Moiré Error Map System for Inspection of Continuously Manufactured Objects

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ABSTRACT

Moiré techniques can be a powerful tool to determine deviation of a manufactured shape from a desired shape. In a traditional moiré system, distorted gratings on an object are viewed through an undistorted grating. The moiré contours that result represent equal depth contours over the entire viewed surface. By generating the moiré patterns in video, it is possible to view the distorted gratings on a test object through a set of gratings that has been distorted by a similar but perfect object. The output is then a set of moiré contours that corresponds to the differences between the two surfaces. This difference or error map eliminates much of the unnecessary information generated in traditional moiré inspection and thus becomes a valuable tool for comparisons between an imperfect test object and a manufacturing standard. We have developed a variable resolution video system for creating this error map using a Michelson interferometer to generate the gratings. We have successfully applied this system to damage detection on long, continuous lengths of pipe by having two side-by-side cameras looking at different sections of pipe and also by having one camera's view filtered with a video-taped recording of an undamaged section of the pipe.

1. INTRODUCTION

Whenever two periodic or semi-periodic structures of similar spatial frequency are overlaid, a moiré pattern is produced. Application of these patterns to surface topography was first suggested in 1874 by Lord Rayleigh[1], but practical applications such as contour mapping[2,3,4,5,6], vibration analysis[7,8], and error mapping[9] did not appear until the middle of the twentieth century. In a traditional projection moiré system, a fixed spacing grating is projected onto a target, which is subsequently viewed through an optical system which contains an identical grating located in an intermediate focal plane, as shown in Fig. 1. In this situation, the moiré pattern seen will be equal depth contours with a contour spacing given by

$$\nabla Z = \frac{mP}{[\tan(\alpha) + \tan(\beta)]}$$

where mP is the grating pitch projected on the target and α and β are the projection and viewing angles as shown in Fig. 1. Variable resolution can be achieved by using interferometers[10,11,12,13] or acousto-optic cells[14,15] to generate the projection gratings. In particular, if a coherently illuminated tilted mirror Michelson interferometer is used as shown in Fig. 2, a set of variable spacing straight line fringes may be projected over a large area with a fringe spacing given by $\lambda/2\phi$, where λ is the wavelength and ϕ is the adjustable angle between the mirrors. Since this system generates only projection gratings, non-traditional (video) techniques have been employed to produce the reference transmission grating in order to generate moiré contours[13,16,17,18].

2. VIDEO MOIRÉ SYSTEM

The interferometer grating projector technique produces the number of resolution elements needed for practical large target moiré work while preserving the variable resolution feature. The problem is how to generate moiré interference patterns in a fringe multiplicative way, in a system which consists of only projected gratings. In the classical projection or shadow system the distorted target grating is viewed through a physical reference grating. This reference grating has the effect of a binary optical filter in that where the grating is opaque no information is transmitted and where the grating is clear information is passed. It is

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the selectively transmitted distorted grating information along with the reference grating information that causes the classical moiré interference pattern. By using a special video processor (a chromakey operation), this situation may be duplicated with a totally projection system. In this operation, part of the video signal from one camera is made transparent to the video signal from a second source. This is accomplished by thresholding on a given signal level within the video signal. The result is to combine two video signals into one, not by superimposing the two but actually replacing part of one scene with another.

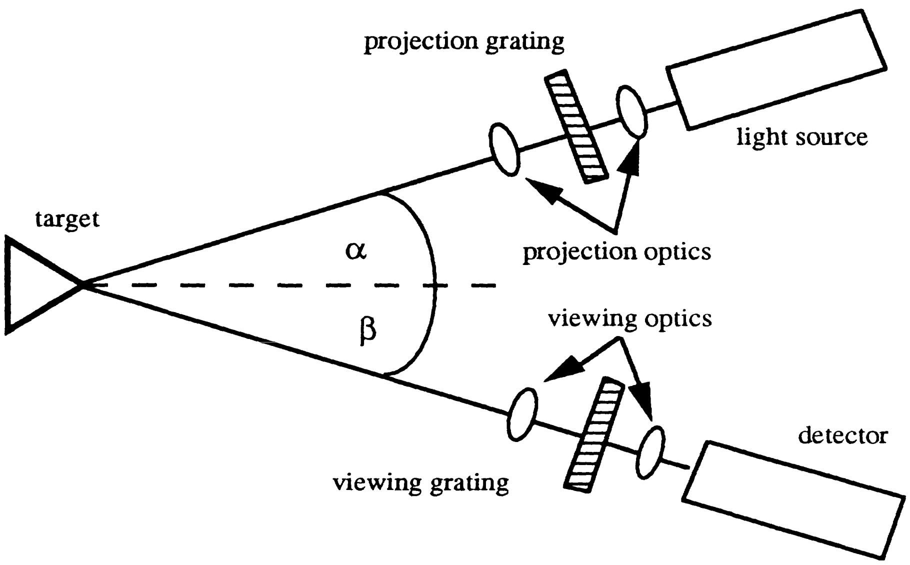


Fig. 1. Projection Moiré

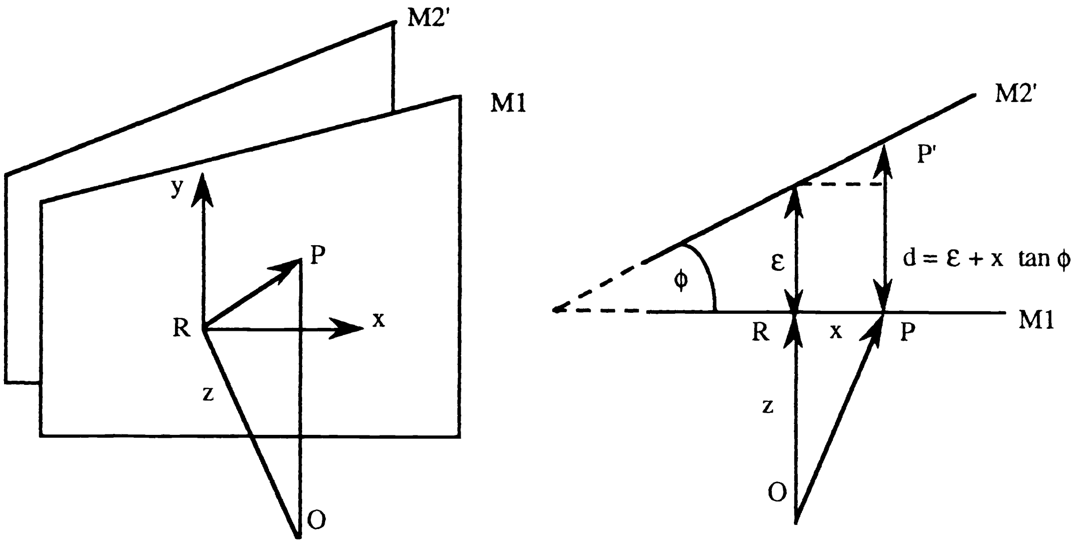


Fig. 2. Tilted Mirrors of a Michelson Interferometer

The video moiré system consists of the Michelson interferometer grating projector with a beam splitter cube which separates the projected beam into the target and reference gratings. Viewing the target and reference surfaces from symmetric angles are two low light level, high resolution (650 TV lines) video cameras. The video signals from these cameras are fed to the video processor. The modified and unmodified video output from the video processor are delivered to two video monitors on which the original and altered video may be viewed simultaneously and to a computer which is used to collect and store data in the form of images via. a video frame grabber board. If the reference surface is a flat plate and if the projection and viewing angles α and β are made the same for the target and reference surfaces, moiré fringes are seen which represent equal depth contours of the target surface. These moiré interferograms are identical to interferograms created by fringe multiplicative methods utilizing physical gratings. The video moiré system set up to generate traditional equal depth contours is shown below in Fig. 3. In this figure, the viewing angles β for both cameras are set to 0°.

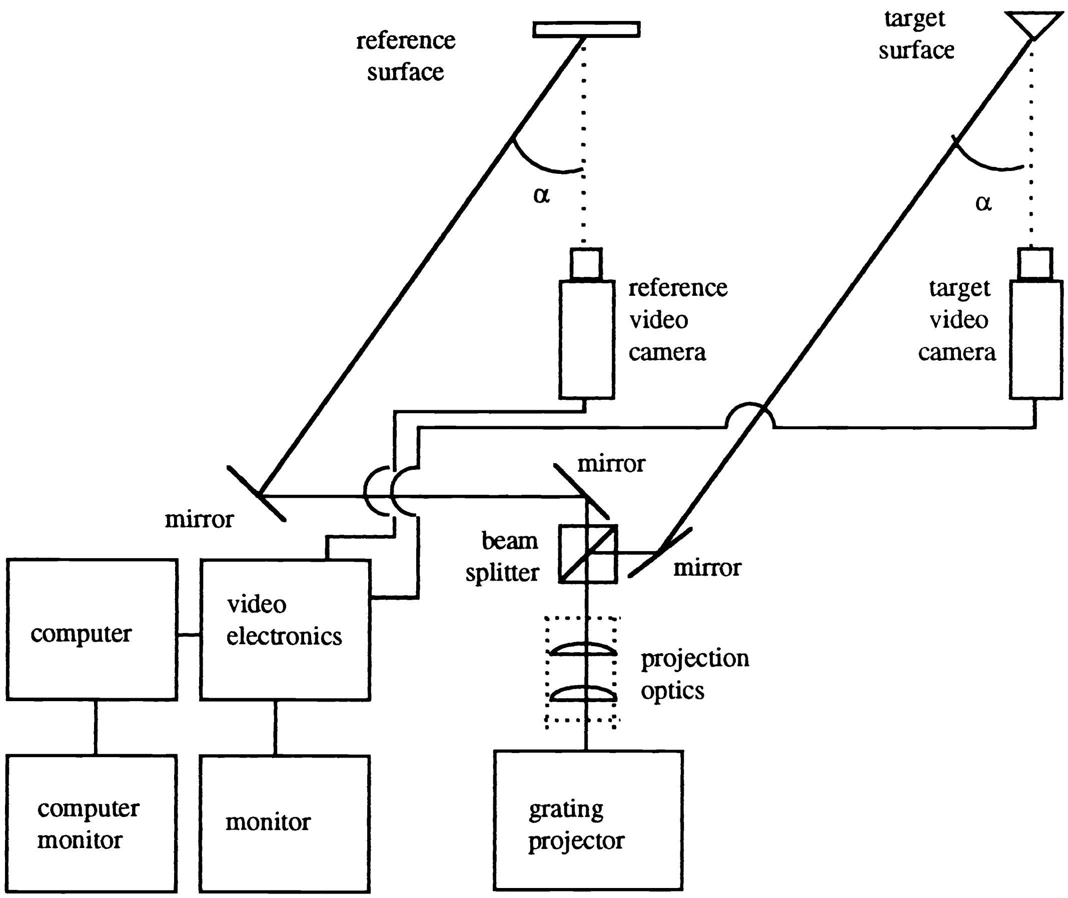


Fig. 3. Video Moiré System

3. CONVENTIONAL CONVERSE MODE ERROR MAPS

A much less publicized method of creating and using moiré patterns than the one discussed above is occasionally used. Often called the converse mode, this method generally involves viewing the distorted gratings on the test object through specially designed (non-parallel line) gratings. Generally, the gratings are designed to produce a simple set of moiré contours when the viewed object is a certain shape. For example, one such system involves designing the gratings so that the resulting moiré is a set of parallel lines if and only if the test object is up to specification[19]. Though the mathematical analysis ordinarily involved in designing these gratings has recently been shown to be reducible[19], it is still not trivial for complex objects. In fact, it requires a complete mathematical description of the object's surface and involves computer-based processing. Perhaps just as significant a problem as that is the issue of grating availability. Since the gratings need to be specifically suited to each type of test object, they are obviously not commercially available and must be designed and fabricated for each different application. This is certainly discouraging to a manufacturer who would like to have a system for inspecting multiple and/or newly developed items.

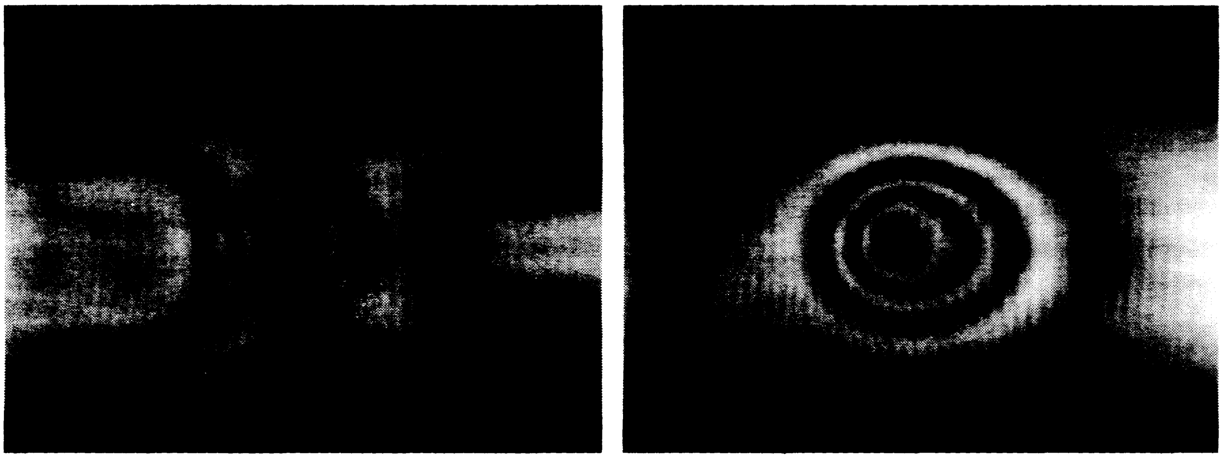
4. VIDEO MOIRÉ ERROR MAP SYSTEM

Probably the biggest advantage of our video method for creating moiré contours lies in its versatility. We can project variable resolution gratings onto virtually any object located at a wide range of distances from the interferometer. Also, we can and do process our images in real-time video (as well as in the computer), giving us many avenues for improvement and unique applications that are not available to conventional moiré systems which rely heavily on "after-the-fact" computer enhancement of the moiré contours. This allows our system to be applied in the converse fashion to what we call the "error map" problem, a simple way to only show contours of a test surface's difference from that of a reference or standard surface (as opposed to the previously mentioned parallel line contours or the equal depth contours over the entire surface, as in conventional moiré metrology.) For this problem, we have two solutions. The first method involves viewing the test (possibly damaged) object's gratings through a set of gratings that has been distorted by a similar but perfect reference object. The second method involves the same basic process, but the image of the reference object with its associated gratings is stored on a high quality video tape that can be played during inspection to create the moiré patterns.

4.1 Perfect Object as Reference Method

The experimental set-up for using a perfect object as a reference or filter for test objects is identical to that given in Fig. 3 for creating ordinary moiré contours, except that the flat plate is replaced by a perfect example of the object to be tested. Just as before, each of the two video cameras captures its respective scene and sends it to the video mixer which performs a chromakey operation to create the moiré contours on a monitor. However, instead of representing the ordinary set of equal depth slices of the test object (where the distance or depth between slices is a function of the grating pitch), the contours represent something potentially much more complicated. They are curves of intersection between the reference surface and the target surface, as before, but the mathematical and conceptual simplicity of the flat plate as one of those surfaces is gone. The intersections are not plane slices, hence each point along an intersection curve is not in the same Z location. They are slices of the target surface that depend on the nature of the reference surface. If, for example, a hemisphere were used as the reference surface, each intersection curve would lie on both the hemisphere and the target surface (hence the term "intersection curve.") Thus, quantitative information about the test object's difference from the standard can only be acquired through the mathematical representation of the reference surface and considerable mathematical analysis of the contours[19]. For complicated test objects (as most real objects are), this would most likely not be feasible. However, if we are simply concerned with knowing if a defect of some order of magnitude is present or not, then this method would be appropriate. If detailed quantitative information about the surface errors is needed, the depth of the contours can be calibrated experimentally for a given surface.

If the target object and the reference object are identical in every way (including position and orientation), then the gratings which are projected onto them are distorted in the same fashion. As a result, no moiré contours appear. If, however, some difference between the two surfaces exists, contours appear. For a fixed grating spacing, as the magnitude of difference between the test and reference object increases, so does the number of moiré contours. Regardless of the surface shape, this basic relationship will hold. Thus, in theory, this system can be used to compare any two surfaces for agreement. The tolerance is set by simply checking for an approximate number of contours or, more likely, for a certain amount of darkness in the screen (our contours appear dark.) If, for example, the number of "dark" pixels on a computer monitor is less than a preset amount, the test object passes the inspection and moves on to allow for testing of the next object. The improvement in useful information between conventional moiré and error map moiré can be seen in Fig. 4.



(a) Ordinary moiré on a dented pipe (b) Error map moiré on the same pipe

Fig. 4. A comparison between ordinary and error map video moiré images on a dented pipe

4.2 Video Tape as Reference Method

In order to create the moiré error map via. the second method, only one video camera is needed. Instead of using a reference camera as the input (i.e. reference grating) to the video mixer to create the moiré, we have used a high quality video tape recording of the gratings on the object. We first make a long tape recording of the distorted gratings on the perfect object, using the target camera. Then, we replace the perfect object with the object to be tested and play the tape back against it to create the moiré in video. This method simplifies the optics somewhat and produces the same results in terms of contours as the first error map method above.

5. INSPECTION OF CONTINUOUSLY MANUFACTURED OBJECTS AND THE MISALIGNMENT ISSUE

From a practical standpoint, alignment (shape, size, position, and orientation in the camera's view) of the test object relative to that of the reference object needs to be quite good in order for the inspection system to be usable. Even slight misalignment can cause problems (i.e. create moiré contours), and thus falsely trigger an inspection system into thinking that a defect in the test object exists. For this reason, our system seems to be particularly well-suited to situations where alignment would be virtually assured. One important example is inspection of long lengths of pipe or other similar structure. By placing the two cameras side-by-side and at the same viewing angle β to the pipe, as in Fig. 5, any displacement or motion the pipe may experience is seen by both cameras in the same way. This greatly reduces the possibility of misalignment between the two camera's views. Note that the reference surface and the target surface are side-by-side sections of the same pipe. If no dent is present in either section, then no moiré contours result and that piece of pipe passes inspection. If, however, a dent is present in either or both of the sections of pipe, then contours appear and that piece of pipe does not pass inspection. Fig. 6 shows three images of a 15mm diameter pipe with a 3mm dent. Fig. 6(a) is in ordinary room light, Fig. 6(b) is with structured illumination (our projected gratings), and Fig. 6(c) is with video moiré error map contours.

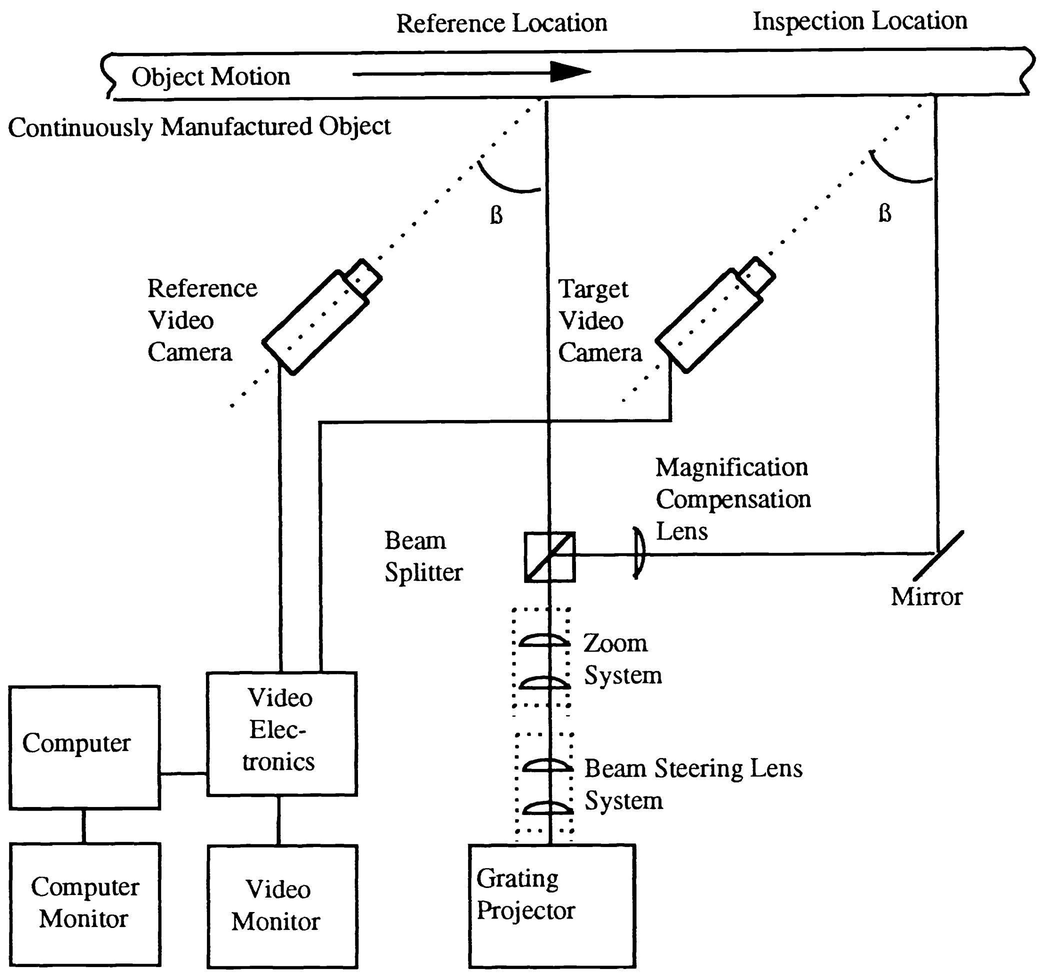


Fig. 5. Video Moiré Error Map Inspection System

(a) Ordinary roomlight on a dented pipe (b) Structured illumination on dented pipe (c) Moiré error map on dented pipe

Fig. 6. A comparison of roomlight and structured illumination to video moiré error map

6. DIRECTIONS FOR DEVELOPMENT OF AN INDUSTRIAL INSPECTION SYSTEM

We have successfully implemented a laboratory version of a video moiré error map inspection system and demonstrated inspection of a continuously manufactured object. Tolerance to object motion and misalignment was large as long as the misalignment did not occur between the cameras. However, several issues must be resolved before a practical industrial system can be built. The need for a diffusely reflective coating and the sensitivity to ambient lighting can both be solved by using low light level cameras with a narrow band filter at the laser wavelength. If fixed resolution inspection is desired, the interferometer and laser could be replaced by a collimated source and a fixed grating, although the laser has the advantage of narrow band illumination which could be useful to eliminate the ambient light sensitivity as mentioned above. In any case, analog processing of the video mixer output to indicate the number of dark pixels could be used to give a pass/fail or quality level sort output for automated inspection. The analog output could also be used to operate a dye gun to mark the defective portion of the pipe or extrusion being inspected.

Another aspect of our system which is easily made use of is the variable resolution feature. This is truly unique to our setup and offers many exciting possibilities. When operating in the error map mode, the resolution of the moiré inspection system could be reduced so that only one error on the surface is resolvable. That error could be repaired, and the resolution could be increased until the next largest damaged area becomes apparent. It could be repaired and so forth until the entire test object is "shaped" to within a high tolerance of the reference object.

We feel that the video moiré error map system holds great promise to become a versatile industrial inspection system and plan to pursue both further applications unique to our system as well as modifications to bring the system to the factory floor.

7. ACKNOWLEDGEMENTS

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