Photogrammetric Measurement of Thermal Deformation of a Large Process Compressor*

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ABSTRACT: High-precision close-range photogrammetry has been employed to measure dimensional changes between the cold and hot running states of a large process compressor to accuracies of close to 0.1 mm. The principal aim of the measurements was to determine the extent of thermally induced alignment changes in the four compression cylinders, because errors in alignment can induce excessive wear on the pistons. In the context of industrial photogrammetry, this project displayed some unique features: first, the compressor in its hot state was running, and therefore vibrating; second, some 20 odd photographs from a 23-cm format close-range camera of 120-mm focal length were required to image the compressor, which covered a floor area of about 8 by 10 m to a height of 3 m; third, a specialized target/illumination scheme was employed; and fourth, the required accuracy was in excess of 1 part in 85,000 of the compressor's principal dimension. In this paper, salient aspects of all phases of the photogrammetric project are discussed.

INTRODUCTION

ONE OF THE OFTEN espoused merits of photogrammetry as an industrial mensuration tool is the effectiveness of the method for measuring large objects of unusual and complex shape. Early in 1984 Geodetic Services, Inc. (GSI) was contracted to perform a photogrammetric survey on such a structure which was of fairly unusual geometry, namely, a large, three stage, four cylinder process compressor which was located in a chemical plant. The aim of the project was to measure to high accuracy (better than 0.2 mm) the deformations in the compressor induced through thermal loading.

A photograph of the compressor, which covered a floor area of close to 8 by 10 m, to a height of near 3 m, is shown in Figure 1. In Figure 2, a plan view is provided which illustrates the layout of the four cylinders, crankcase, main shaft, and motor. As can be appreciated by the reader, any maintenance on the compressor which requires removal of cylinder heads, pistons, etc., when considered along with the accompanying compressor downtime, is an extremely expensive operation. One of the primary maintenance concerns centers on alignment. Departures from true alignment in the cylinders, crosshead guides, and crankcase can cause excessive wear in the compression cylinders, especially of the pistons.

Initial alignment of the compressor components is carried out when the unit is not running, a state that will be referred to as the 'cold' condition. In its 'hot' running state, a considerable degree of thermal loading is applied. The primary concern in this regard is that localized deformations and alignment changes resulting from thermal loading can lead to excessive wear, and eventually the necessity for earlier-than-scheduled maintenance. To quantify the extent of misalignment, it is necessary to measure the thermal displacements which areas of the compressor experience during the 'cold' non-running to 'hot' running transition.

As a non-contact three-dimensional mensuration tool photogrammetry would, at first sight, seem to be very applicable to the task of measuring thermally induced displacements at critical points on the compressor. However, one crucial fact had to be accounted for: In its hot running state the compressor is subjected to significant vibration, the amplitude of vibrational excursions at some points being larger than the anticipated thermal displacements that were to be measured. Coupled with this problem was the complex shape of the compressor and the need to measure the entire unit, rather than looking at localized areas such as individual cylinders. Notwithstanding these complications, a practical photogrammetric measuring scheme was adopted and two sets of measurements of the compressor were carried out to an accuracy which for the bulk of the 100 or so targets exceeded 1 part in 85,000 of the structure's principal dimension.

In this paper the photogrammetric deformation survey of the four-cylinder compressor is discussed.

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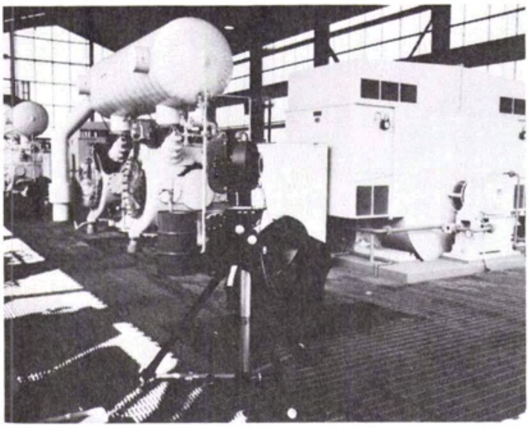

FIG. 1. The compressor, with the CRC-1 in the foreground.

Among the aspects outlined will be the network design phase, targeting, the specialized imaging scheme adopted, and salient results of both the photogrammetric data reduction and subsequent deformation analysis.

THE PHOTOGRAMMETRIC SURVEY

NETWORK DESIGN

For the photogrammetric measurement of thermally induced deformations in the compressor, the accuracy specifications were that the network should exhibit sufficient precision such that the computed standard errors of point displacements would be at the 0.2-mm level. Because the final variance of a displacement vector at a point is computed as a function of the summation of the covariance matrices obtained in the 'hot' and 'cold' measurements, one can infer at the planning stage a target mean standard error for the object point coordinates at each measuring epoch. Under the assumption that the photogrammetric networks will be of basically the same geometry at the two measuring epochs, a target mean XYZ coordinate standard error of $\overline{\sigma}_c = 0.12$ mm was established as a one-number accuracy criterion.

Among the important questions that must be addressed regarding the design of the network are the following: What photographic scale is required? What focal length is optimum to balance considerations of field of view and depth of field versus photographic scale? How many camera stations are required? And, in addition to the targets established for deformation monitoring purposes, will further 'tie points' be required? Turning first to the selection of photographic scale, the following empirical formula can be employed:

$$\overline{\sigma}_c \simeq qS\sigma \tag{1}$$

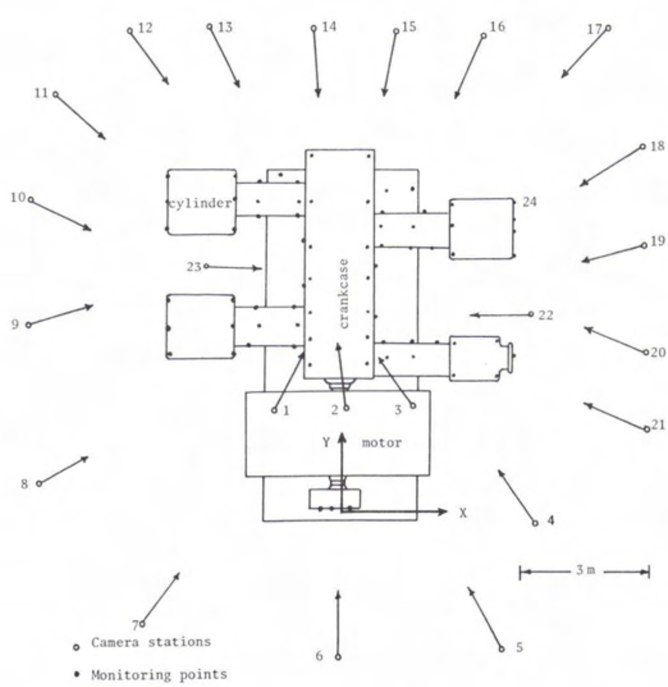

FIG. 2. The geometric configuration of the 23 camera stations.

Here, S is the scale number, σ is a global estimate of the standard error of image coordinate measurements, and q is a factor whose magnitude is related to network geometry (see, for example, Fraser (1984)). As stated above, a target magnitude of the mean XYZ coordinate standard error $\overline{\sigma}_c$ was established as being 0.12 mm. When coupled with a film reader precision of $\sigma = 3$ μm and a q value of about 0.8, a design imaging scale of 1:50 is obtained.

As can be seen from Figures 1, 2, and 3, the three stage, four cylinder process compressor constitutes a reasonably complex object as far as photogrammetric measurement is concerned. The space available about the compressor for camera locations dictated use of a camera of very wide angular field, and the required photographic scale necessitated the use of a large photographic format. Accordingly, the only practical choice of camera was limited to a GSI-built CRC-1 microprocessor-controlled photogrammetric film camera of 23- by 23-cm format (Brown, 1984) with a 120-mm lens. The field of view of this camera is close to 90° in the x and y directions. A photograph of the CRC-1 with a 120-mm lens and accompanying ring strobe is shown in Figure 4.

Having selected an appropriate camera and imaging scale for a project, the next step is to determine a suitable network geometry. At GSI this phase of the design process is carried out using the technique of computer aided design. A graphics-based network simulator which forms an integral part of GSI's turnkey close-range photogrammetric system STARS is used by the planner to design, in an interactive fashion, an optimal camera station and target array geometry for a particular network. Through the generation of trial data sets, the simulator is used not only to plan such aspects as camera station layout, but also to produce measures of precision (e.g., $\overline{\sigma}_c$) from which the planner can immediately ascertain whether his design will meet user-specified accuracy criteria. For further accounts on aspects of photogrammetric network design and simulation the reader is referred to Fraser (1984) and Gustafson and Brown (1985).

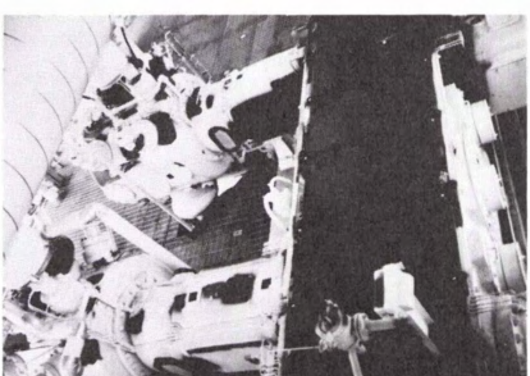

FIG. 3. The crankcase housing and two west-facing cylinders.

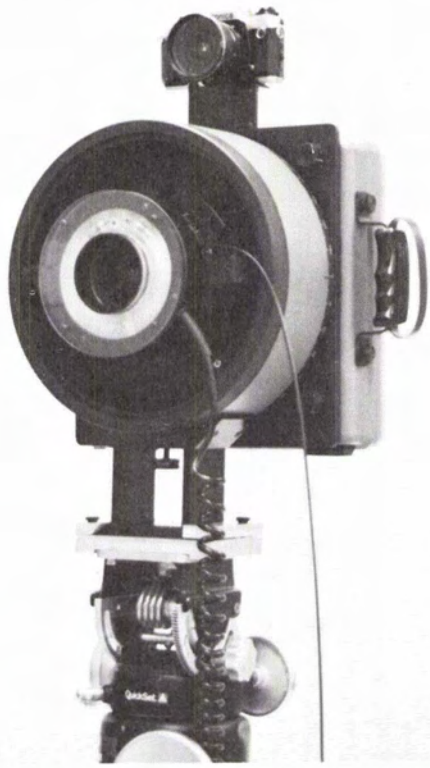

FIG. 4. The CRC-1 camera with 120-mm lens and ring strobe.

At the compressor project planning stage, two features of the STARS simulator proved most useful. The first was the projection on the terminal screen of the scene (targets only) that would be imaged from a particular camera station. By examining the design 'photograph,' the planner could ascertain visually which points would be imaged and which would be either obscured or out of the field of view. Camera aim point adjustments could then be made interactively until the optimum view was achieved. The second feature called upon was depth of field computation. Although a mean image scale of 1:50 was adopted, scale in any one photo ranged from about 1:20 through to 1:100. Thus, depth of field considerations were crucial. In a normal project where comparator measurements are carried out manually, a circle of confusion of up to say 0.1 mm is usually acceptable. Beyond this, however, loss of definition in the image can adversely affect pointing accuracy. Even at an f-stop of 45 it was deemed necessary to ignore images of points in either the extreme near or far fields at a number of camera stations.

The design camera station layout for both epochs of measurement is shown in Figure 2. This geometry was achieved in the 'hot' case but, in the 'cold,' station 23 was not occupied. Except for the camera positions (stations 1-3) on the top of the motor housing which were some 4.5-m above the floor, and stations 13-16 which were 3.7-m above the floor, camera heights were about 2.5 m. Again, because of the complexity of the target layout (points on the ends, sides, and top of the crankcase housing, cylinders, and shaft support), there was a considerable variation in the anticipated object coordinate accuracy for different target areas. Although a mean standard error value of $\overline{\sigma}_c = 0.1$ mm was obtained at the network simulation stage, standard error estimates ranged from $\sigma_{XYZ} = 0.04$ mm for points on the crankcase housing which were imaged on ten or more photographs to $\sigma_{XYZ} = 0.25$ mm for a few targets which were imaged with poor geometry in only two or three exposures. (The standard error σ_{XYZ} is simply obtained as the square root of the mean of the coordinate variances σ_X^2, σ_Y^2, and σ_Z^2.)

Although not shown in Figure 2, a number of temporary 'tie points' were established on and around the motor housing in order to provide a strong geometric connection between the points on the support at the end of the shaft, and those on the cylinders. In all, some 100 targets were to be triangulated at each measuring epoch, although only about 70 of these were to act as deformation monitoring points.

Targeting

For the majority of industrial photogrammetric measuring tasks, planar targets are employed. These generally comprise either a white dot against a black background or a retro-reflective dot and annulus configuration (e.g., Brown, 1980). However, planar targets have one obvious limitation: They can only be viewed from a finite range of directions. Typically, an incident ray must subtend an angle of 35° or greater with the plane surface of the target. With retro-targets an angular tolerance of 25° is usually a practical limit. One need only glance at the camera station configuration shown in Figure 2 to realize that planar targets would not be appropriate for the compressor project.

When a photogrammetric network calls for a target that must be imaged from a host of very different directions, only one practical option is normally available: the use of reflective spheres. Spherical targets will always return an image which lies on the ray through the sphere's centerpoint so long as one employs on-axis illumination. With the CRC-1 a ring strobe unit mounted about the lens serves this purpose. The arrangement is illustrated in Figure 4. To serve as deformation monitoring targets on the compressor, half-inch diameter steel tooling balls (with precise sphericity) were employed. These targets were epoxied in countersinks in order to ensure stability. For tie and scale control points, ball targets were also employed.

Photography

Two epochs of measurement were to be made. Initially, the compressor would be photographed in its 'cold' state, and, following a week of running, it was to be imaged in its thermally stable 'hot' running state. It was envisaged that the 'cold' measurement would be relatively straightforward as far as photography was concerned, but with the 'hot' case one special problem had to be solved. When running, the compressor vibrates with a frequency of around 10 Hz. Although the amplitude of this vibration is essentially insignificant for more dimensionally stable components of the compressor (e.g., the crankcase housing), it can reach in excess of 0.1 mm on the four cylinders. How then does one measure a deformation vector whose magnitude is potentially less than the harmonic displacements caused by vibration?

The answer to this potentially vexing problem lay in the use of an electronic flash unit, a Balcar Monobloc 2 in this case, which would provide multiple stroboscopic flashes to a frequency of 25 per second. The idea was to expose the vibrating object targets with six flashes per second for a period of about eight seconds. At six per second, the flashes would be out of harmonic phase with the compressor. Although a single flash of 350 J would not in itself yield a satisfactory point image on a tooling ball, the cumulative effect of the 50 or so strobe flashes would provide an image in the form of a spread function, the centroid of which would be the mean (i.e., zero vibration) position of the target.

Implementation of the multiple strobe approach proved very successful for the two sets of compressor photography, and vibrational excursions in the hot running state did not degrade the imagery to a measurable degree. In fact, for both the 'hot' and 'cold' cases, sharp point images of between about 60- and 200-μm diameter were obtained using the ball targets. Figures 5 and 6 show two sample frames from the photography; unfortunately, neither image shows up the targets too well at this scale.

Photogrammetric Data Reduction

Following the image coordinate measuring phase, which was carried out in monoscopic mode to an accuracy of about 2 μm on a Kern DSR-1 analytical stereoplotter, object target points were triangulated using the self-calibrating bundle adjustment program STAR. Other than the provision of redundant scale measurements, no external object space control was employed.

For the 'cold' case, the photogrammetric triangulation yielded a mean standard error of $\overline{\sigma}_c = 0.11$ mm for the object point XYZ coordinates. As anti-

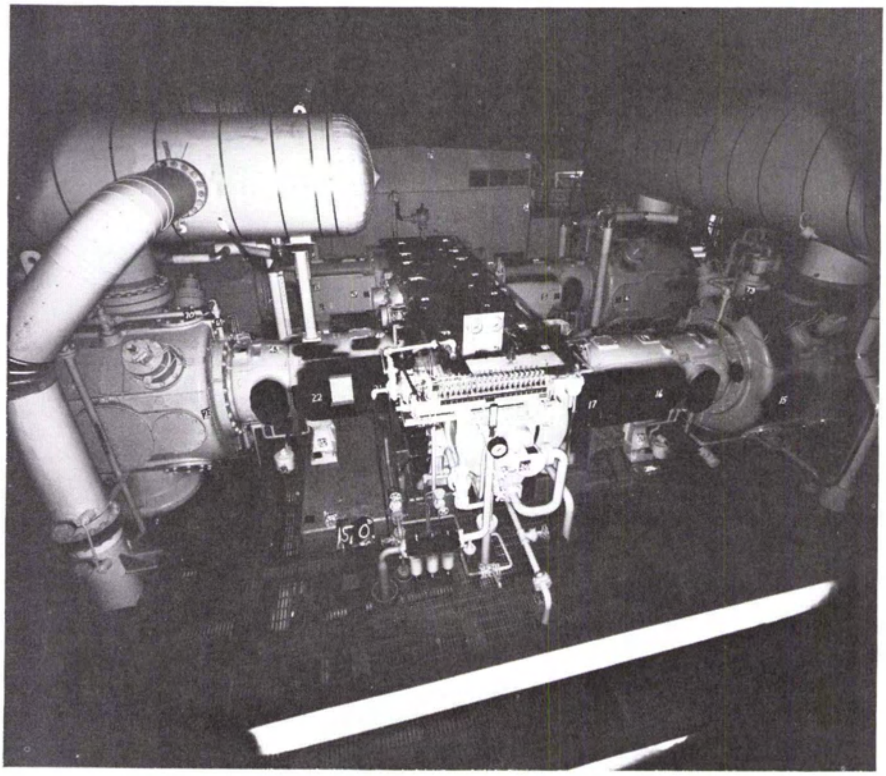

FIG. 5. Photograph from camera station 15, 'cold' case.

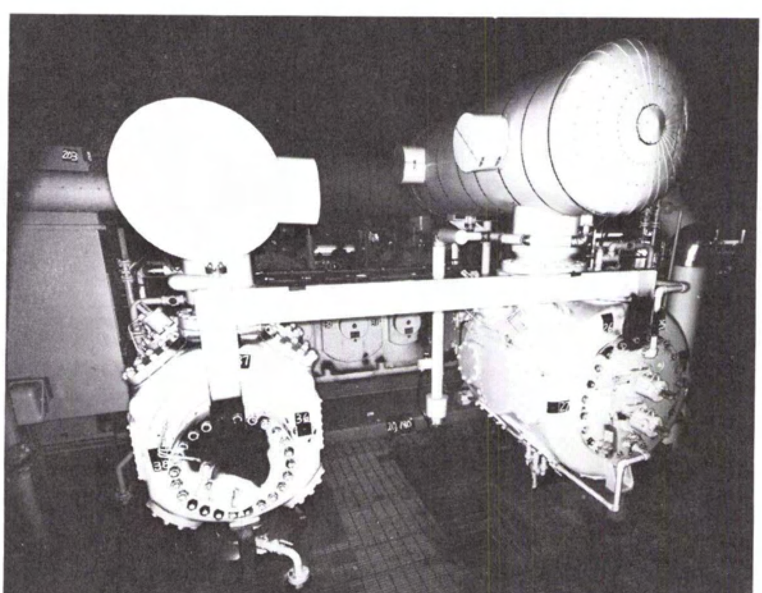

FIG. 6. Photograph from camera station 20, 'hot' case.

cipated from the network design simulations conducted, a few of the targets exhibited poor reliability. These were points which had only two or three intersecting rays, with poor intersection geometry. The mean positioning accuracy obtained in the 'hot' measurement was $\overline{\sigma}_c = 0.10$ mm. In both measurements the precision in the Z coordinate (vertical) was close to 0.02 mm better than in XY (the horizontal). Overall, the results represent in each case a positioning accuracy of better than 1 part in 85,000 of the compressor's principal dimension. For points on the top of the crankcase housing, the accuracy approached 1 part in 240,000.

When it is considered that in the 'hot' case the compressor is subjected to vibrational excursions of the targets, a smaller triangulation closure error would be anticipated for the 'cold' measurement. However, quite the opposite result was found. The RMS value of image coordinate residuals was 4.1 μm for the cold and 3.0 μm for the 'hot.' Moreover, numerous residuals in the 'cold' triangulation were of magnitudes greater than 10 μm, whereas no such large closure errors were found in the 'hot' measurement. On examining these residuals more closely, it became apparent that in its cold, supposedly static state, the compressor was actually not stable at all. While it was not possible to reliably infer the magnitude of point movements which occurred during the 2 to 3 hour period of photography, it was possible to isolate the areas of maximum instability, these being the two cylinders on the west side of the compressor. Photography commenced shortly after sundown and during the following few hours the temperature dropped almost 10°C. Also, just prior to sunset the two west-facing cylinder heads were in direct sunlight. Thus, it appears that the point displacements were thermally induced through differential cooling in the cylinders and crosshead guides. Although there had been previous evidence of the magnitude of diurnal movements in the cylinders, that being obtained by direct optical measuring techniques, this information was not made available to GSI and the photography was carried out under the assumption that in its cold non-running state the compressor was indeed static. The interesting paradox was then that the object was really first in a cold but dynamic state whereas when hot and running it was thermally quite stable.

ANALYSIS OF DEFORMATIONS

In seeking to ascertain the extent of thermally induced deformations in the compressor, it was necessary to determine the extent to which the shape of the object had changed from the 'cold' to the 'hot' state. It was not required that the amount of uniform thermal expansion be quantified, but the magnitude of out-of-plane point movements and other differential shape deformations due to thermal effects were sought.

When computing point displacements simply from coordinate differences, it is essential that both epochs of XYZ object coordinates have the same datum, i.e., the respective reference systems have the same origin, orientation, and scale. The choice of an appropriate datum is not always a straightforward operation, especially in the case of 'relative' as opposed to 'absolute' deformation monitoring networks (see, for example, Fraser and Gruendig (1985), Niemeier (1981), and Mierlo (1981)). However, it is always possible to change datums through rigid body transformations coupled with S-transformations for covariance matrices.

In order to highlight differential movements induced in the cylinders and shaft support with respect to the crankcase housing, a common datum comprising six target points on top of the housing was selected. The XYZ coordinates for the 'hot' and 'cold' cases were then transformed into this datum through a three-dimensional similarity transformation. The RMS values of the point displacements in the three coordinate axes for the six common transformation points were as follows: 0.11 mm in X, 0.20 mm in Y, and 0.11 mm in Z. The larger RMS value for Y can be explained by the fact that the top of the crankcase consisted of adjoining rectangular steel plates rather than a single piece of metal. Thus, differential thermal influences in the Y direction could be expected to be significantly greater than in the X or Z directions.

Once the two sets of XYZ coordinate data had been brought into the same datum, point displacements were computed from coordinate differences. Deformations at the 67 monitoring points ranged from a displacement of 2.5 mm at point 24 (see Figure 2) down to non-significant movements of less than 0.2 mm. In computing the magnitude of displacement vectors, the effect of uniform heating of the compressor was first subtracted. In general, point movements were at the 0.8- to 1.2-mm level, and thus were clearly statistically significant at the 95 percent confidence level. Plots of the measured deformation indicated consistent trends, especially in changes of the alignment of cylinder heads with respect to both the crosshead guides and the axis of the crankshaft. With the number of monitoring points established, it was possible to build up a reasonably comprehensive picture of the three-dimensional pattern of thermally induced deformations in the compressor.

Some hours prior to each period of photography a leveling survey was carried out independently of the photogrammetric measurements. Standard optical techniques were used to level selected targets to an accuracy of about 0.07 mm. Following the photogrammetric data reduction, it was therefore possible to compare the Z-displacements computed with those obtained in the leveling survey. Because of the fact that the cylinders displayed diurnal movement, the results comparison was restricted to

17 points on and near the crankcase. An RMS value of the Z-displacement discrepancies between the leveling and the photogrammetric measurement was 0.11 mm. This result provided an independent check on the photogrammetric triangulation accuracy, albeit in only one coordinate axis. It was encouraging to note that the RMS discrepancy was smaller than the 0.15-mm mean standard error of the photogrammetrically measured target point displacements.

CONCLUDING REMARKS

GSI has been involved in high-precision industrial photogrammetric mensuration for two decades, measuring objects ranging in size from small assembly tools to 100-m diameter antennas. As far as degree of difficulty goes in the range of measuring tasks carried out, the three-stage compressor certainly ranked as one of the more difficult jobs encountered. Three principal factors contributed to the complexity of the photogrammetric measurement: The shape of the object and the sometimes awkward positions where deformation monitoring points were sought; the fact that in its running state the compressor was vibrating; and, finally, the desire that the entire compressor, including the crankshaft support behind the motor, be surveyed in the one coordinate system. The latter requirement accounted for the addition of extra camera stations simply to tie in the crankshaft support which was not intervisible with the rest of the compressor due to the motor housing.

Optical techniques have often been employed in deformation measurements of such compressors. Alignment surveys in both the horizontal and vertical yield information on out-of-plane movements at critical points. From these one-dimensional displacement measurements the three-dimensional movement of selected sections of the cylinders can be computed. What photogrammetry provides to supplement optical measurements is a comprehensive three-dimensional measurement of thermally induced deformations which cover the entire compressor. At every monitoring point a displacement vector can be computed and its components resolved in three axes rather than one. Additionally, the density of monitoring points established does not impact on the photogrammetric data acquisition time in the field, and only moderately influences the image mensuration and data reduction time.

Nowadays, one finds in the literature an ever increasing number of reports dealing with applications of non-topographic photogrammetry to a host of high-accuracy non-contact, three-dimensional measuring tasks. The purpose of this paper has simply been to illustrate yet another of the diverse measuring applications to which industrial photogrammetry can be applied.

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