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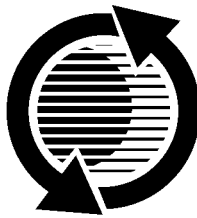LMS International

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Measuring a Geometry by Photogrammetry: Evaluation of the Approach in View of Experimental Modal Analysis on Automotive Structures

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ABSTRACT

The very first step when starting an experimental modal analysis project is the definition of the geometry used for visualization of the resulting mode shapes. This geometry includes measurement points with a label and corresponding coordinates, and usually also connections and surfaces to allow a good visualization of the measured mode. This step, even if it sounds straightforward, can be quite time consuming and is often done in a rather approximate way. Photogrammetry is a technique that extracts 2D or 3D information through the process of analyzing and interpreting photographs. It is widely used for the creation of topographic maps or city maps, and more and more for quick modeling of civil engineering structures or accident reconstruction.

The purpose of this paper is to evaluate the use of this technique in the context of modal testing of automotive structures. After a short description of the method, the approach will be evaluated with regard to several criteria: accuracy, convenience, cost, required time. Two cases will be shown: the measurement of an exhaust, on which the measurements will be compared with a classical co-ordinate measurement machine and the measurement of a body in white, for which the measured points will be correlated with points of an FE model.

The study will show that photogrammetry is indeed an interesting approach to measure the geometry. The main benefits are the increased accuracy compared to manual measurements, short immobilization time of the object, simplicity, enhanced visualization and low cost.

INTRODUCTION

When doing an experimental modal analysis, one of the first tasks the test engineer must do, is the definition of the points to be measured, the identification of these points on the structures, and the creation of a 3D model representing these measurement points. Two different scenarios are possible:

- The test engineer has a CAD or Finite Element model and wants to use this information for the test preparation: he will have to select the points to be measured on the computer model, to reduce the computer model to this limited number of measurement points (and related visualization elements such as lines or surfaces) and finally to locate them on the real structure.
- The test engineer determines the location of his transducers on the structure, but will need good estimates of the co-ordinates of these points in order to make a realistic 3D model for visualization or for comparison with FE results. The most used approach is still the "ruler" method: points and co-ordinates are measured manually with a ruler, yielding usually very approximate models.

A lot of different 3D digitizing systems exist, based on different technologies. "Classical" 3D Coordinate measurement machines used in metrological rooms for dimensional verification of mechanical parts, are more and more replaced or complemented with 3D digitizers, also used for reverse engineering, consumer-oriented products or high-end special effect for the movie industry.

3D Digitizing systems can be categorized in two basic groups [1]: mechanical based systems and camera based systems. But even this description has to allow for hybrid designs or does not cover all existing systems. Mechanical based systems usually depend on following the hand-guided or automated movement of a mechanical probe around the object in question. Electro-optical or electromagnetic sensors supply the positional information to data acquisition software. For experimental modal analysis, the conventional CMM

systems are usually not really suited, because they are expensive and often not mobile. However systems based on articulated arms (FaroArm, Romer, …) are more practical, because more mobile. A hybrid version of such a system, using a mechanical probe but with acoustical emitter and receivers exists and is already used in the field of experimental modal analysis [2].

Camera-based systems usually work by illuminating a point or stripe on the object in question. Some systems use lasers, while other equipment uses infrared, ultraviolet, or structured or unstructured white light. Generally, CCD sensors capture nuances of the reflected lights and control software interprets the light patterns, using principles of triangulation, time-of-flight, phase shift, and/or wave interference information to determine coordinate positions. These kind of systems usually generate high-density point or surface information, with the disadvantage that it is more difficult to locate specific points, such as is typically needed for a modal analysis.

A lot of other systems can be classified as hybrid, handheld, and hard-to-classify.

1. PHOTOGRAMMETRY

1.1 PRINCIPLES OF PHOTOGRAMMETRY - Photogrammetry is the technology of obtaining information (whether it be 3D data or qualitative data) through the process of analyzing and interpreting photographs.

All our topographic maps and many of our city maps are produced with photogrammetry. The photographs are taken with large-format film cameras from low flying aircraft and are then used in an instrument called a stereoplotter to produce the map data. Photogrammetry is not limited to film cameras. Video cameras, still video cameras, digital cameras and normal consumer 35mm cameras can all be used to perform 3D measurement using photogrammetric techniques. It is also not limited to topographic applications and is used more and more for the measurement of 3-dimensional objects [3].

The use of video or photography also allows one to document other characteristics of the object such as surface color, texture and general condition. A high-speed camera can be used to capture an object in motion and hence photogrammetry can be used for vibrating and moving objects unlike most other 3D measurement technologies.

Once the photographs are taken of the object being measured, one can make as many or as few measurements as necessary. If only a few measurements are needed, they can be done quickly. At a later date if more extensive measurements are needed, the photographs can be reused to get these measurements without revisiting the site or object.

Photogrammetry includes the following basic steps:

A. One or more views of the object is captured as an image (on film or on an electronic image sensor).

B. The points are marked and referenced at distinct features on the object (a,b,c)

C. The software calculates the position of the camera for each photo (use of the Descartes formula ; 6 points for each photo are necessary).

D. The software calculates the intersection of light rays from each of the photo positions out into 3D space (3 points are necessary between at least two photos to find the camera relative positions).

E. Using multiple photographs one can capture the whole object or scene.
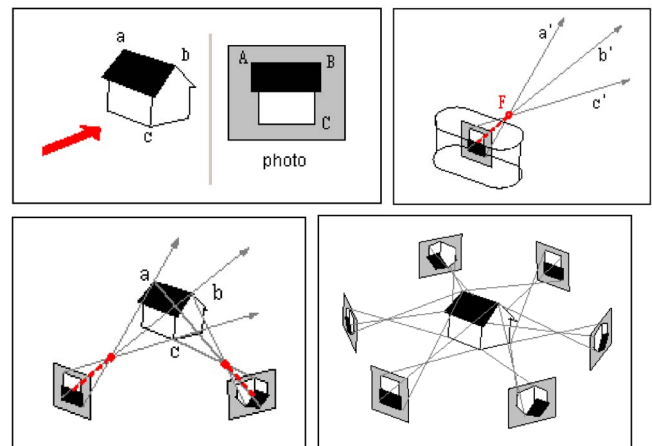

figure 1: principles of photogrammetry

1.2 PHOTOGRAMMETRY APPLIED FOR MODAL ANALYSIS – The evaluation of the applicability of photogrammetry for modal testing was done with a commercial photogrammetry software package, PhotoModeler Pro from EOS systems [4] (Rev 3.1 and beta-release of Rev 4). Using this software package, following steps are required:

Step 1 : The software requires a *description of the camera* (focal length, imaging scale, image center and lens distortion) used to take the photographs. This description needs to be *created only once* and is used for every subsequent project done with this camera (for a given configuration). The most accurate solution here is to do a full camera calibration. This can be done by taking six or more photographs of a printed calibration pattern and processing them with the dedicated calibration program.
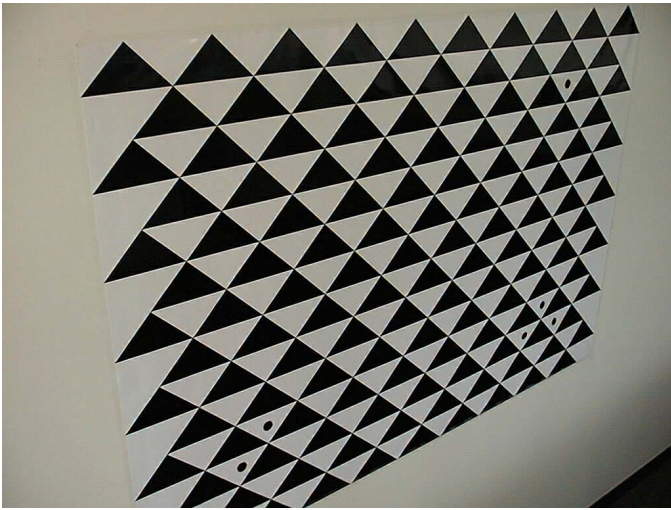
figure 2: example of a photograph of the calibration sheet

figure 3: cross-referencing points on different views

Step 2 : For modal testing, it is advised to mark the point on which the transducers(accelerometers) will be placed. Ideally this should be done before shooting the photographs. The use of high-contrast markers will enhance the quality of the result. In this study, no specific retro-reflective targets were used, but square black and white target were printed on adhesive paper and applied on the structure (see figure 3).

Step 3 : Multiple photographs of each point need to be made. These photographs must meet certain geometrical constraints. For this reason, the positions of the photographs need to be thought out.

Step 4 : The photographs need to be imported. Most digital cameras have a convenient way to import the photographs to the PC. The photogrammetric software will recognize most usual formats.

Step 5 : The targets (points that are going to be measured) need to be marked. Marking is the process of creating and positioning an object on a photograph. This can either be done manually, by mouse-click on the appropriate location on the photograph or in an automated mode. For the latter case, circular targets with a high contrast with the background are required..

Step 6 : In the next step, the points need to be referenced. Referencing is the process of telling the software that two points, marked on two different photographs, represent the same physical point in space.
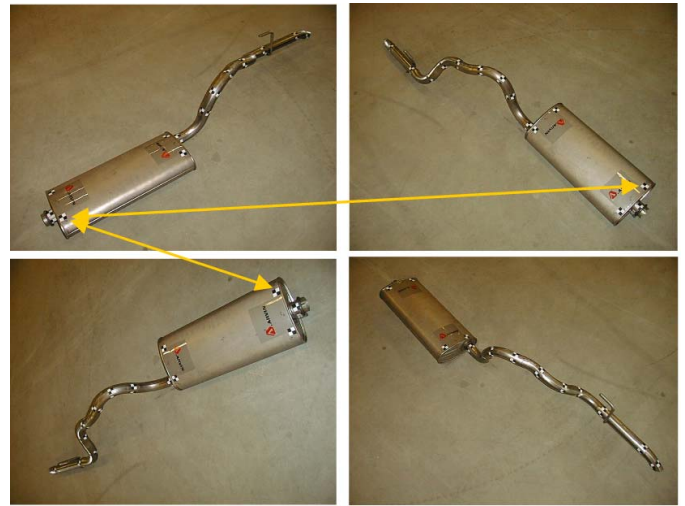
Step 7 : Using this information, the software will first calculate the relative camera positions, and then recalculate all the 3D coordinates of the points.

Step 8 : View, measure or export the resulting 3D data to the Modal analysis software package. Additional objects such as lines, surfaces can be added between the identified points. This ca be done on the photographs (see figure 7) or on the resulting 3D model. For larger projects, steps 4 to 8 might be repeated a number of times, in order to limit the number of photographs that are handled simultaneously (more convenient to the user in order not to get lost)
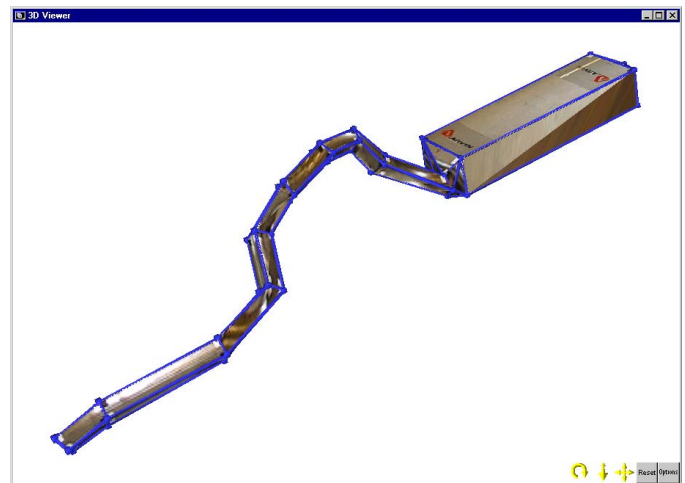

figure 4: The resulting 3D model with lines and surface texturing

2. CONVENIENCE AND ACCURACY

2.1 GENERAL GUIDELINS - A first point to be studied is the convenience of the method. Of course, the convenience is a general notion and it can only be evaluated after a few tests.

As a geometry measurement is not the main goal and main expertise of the operator when doing a modal test, it is important that the software is intuitive and user-friendly. The different tests showed that this was really the case. Another critical point that the operator should be aware of is the importance of taking good shots. Following practical guidelines should be followed

1. *Try to get the angles between the shots as close to 90°*
2. *Try to get all important points on at least 3 photographs*
3. *Try to get as much overlap between adjacent photographs*
4. *Try to get photographs from both above and below the object*
5. *Take many photographs of the object but use only 4 at the start until you determine you need others*
6. *Measure the distance between two clearly visible points.*

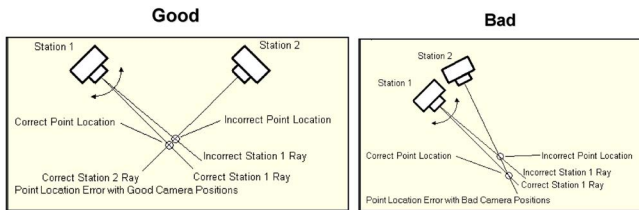The guidelines 1 and 4 are a consequence of the following problem (figure 5):

figure 5: Influence of bad camera angles

In the both cases, Station 1 has the same position and the same angle error. On the other hand, in the right figure, Station 2 is close in angle to Station 1. This small error is multiplied and the resulting position of the 3D point is much farther off the mark.

The closer the angle between the light rays is to a right angle (90 degrees) the smaller any possible error will be.

Guidelines 2: Nobody can mark a point perfectly, and occasionally the point you wish to identify is fuzzy or hard to position exactly in the photograph. If the photogrammetric software has good Camera Station positions, but imprecise point locations in the photographs, the projected 3D point will be inaccurate. To reduce this problem, it is important to mark a point in three or more photographs. That way, if the point was positioned incorrectly on one of the photographs, the other two photographs could compensate for it. If it is marked on only two photographs, marking errors cannot be found and will cause an inaccurate 3D point to be created.

Guidelines 3 : you need points marked in two or more photographs. Photographs taken side by side should contain many of the same object features and points. The more references across photographs for each point, the better, but the user wishes to minimize the marking task since it takes time. To balance these two, it is best if the photographs overlap as much as possible.

The figure below shows a case in which two photographs have no overlap because of an obstruction. Photographs at Station 1 and share no common points on the object. This measurement can be done, but some of the points marked will appear on two photographs only. These points near the wall will probably have lower accuracy than the rest of the measurement because of a lack of redundancy and poor strength in the geometry of the network of points and cameras.
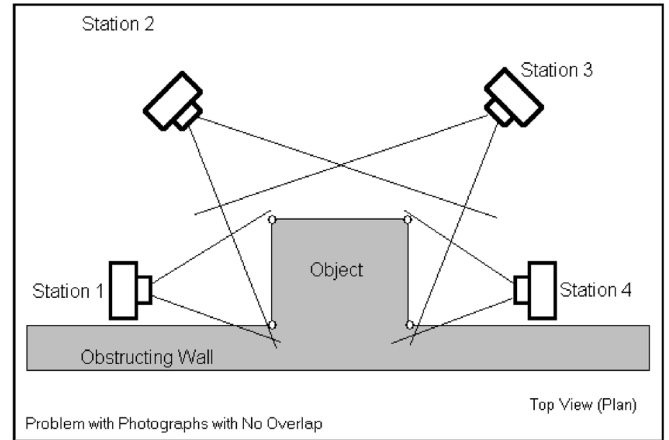

figure 6: problems of insufficient overlap

One way to get around the problem presented in this figure is to add a fifth Camera Station located between Stations 1 and 4 but above the wall, looking down. This fifth Camera Station will have overlap with Stations 1 and 4 thereby increasing the accuracy of the top points near the wall. It might also share some points with Stations 2 and 3 increasing the redundancy and network strength even more.

In practice, it is not required to follow this guidelines strictly, but the closer the requirements are met, the easier the measurement process will be and the more accurate the measurements. Angle, distance and height should be changes as much as possible when taking photographs.

2.2 ACCURACY – The accuracy of a measurement project is dependent on :

- the quality of the calibration of the camera
- the resolution of the camera
- the geometry of the camera positions (cf. the previous photography guidelines)
- the precision with which the user marks the features as they appear in images

If the user takes the following precautions, the errors will be minimized and measurement accuracy maximized :

- ensure that a well-calibrated camera is used for the project,
- maximize the number of photographs that each point is marked on,
- ensure that all points appear on three or more photographs,

- minimize the number of points that appear on only two photographs,
- ensure that the angle between the camera positions is as close to 90 degrees as possible,
- ensure that for points marked on only 3 or 4 photos, these photos are taken with the camera positions as close to 90 degrees as possible,
- make sure the project has at least 25 points and the photographs have good coverage,
- ensure all point and line markings on the images are precise, and
- do not guess at a point location if it cannot be seen, is not distinct, is fuzzy or is hidden by some other object.

2.2.1 Influence of the camera positions and number of photos - The importance of the camera positions has been studied on exhaust on which 15 points were measured. Different test cases , using a different number of photographs and different camera positions are considered in order to quantify the effect of these parameters. All tests were done with a low cost commercial digital camera (AGFA e-photo 1280 digital camera with "PhotoWise" software to transfer the photographs to the PC), using 1024 x 768 resolution.
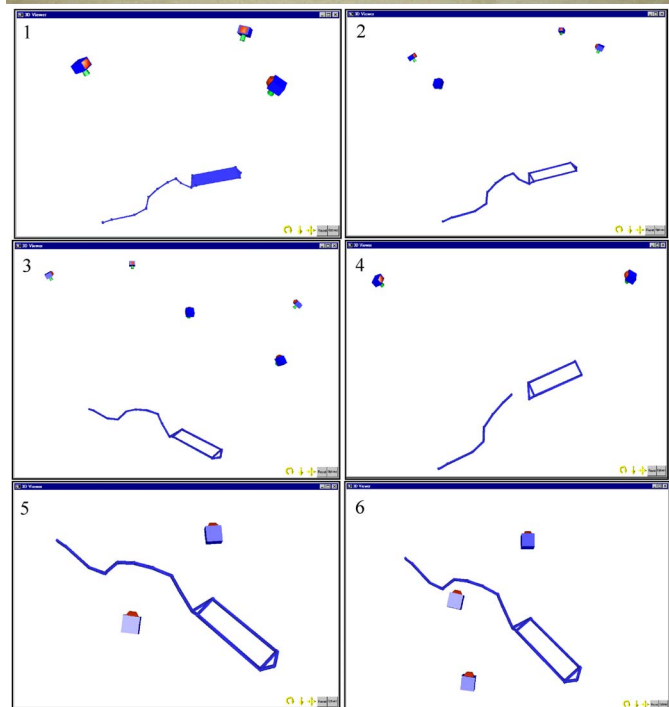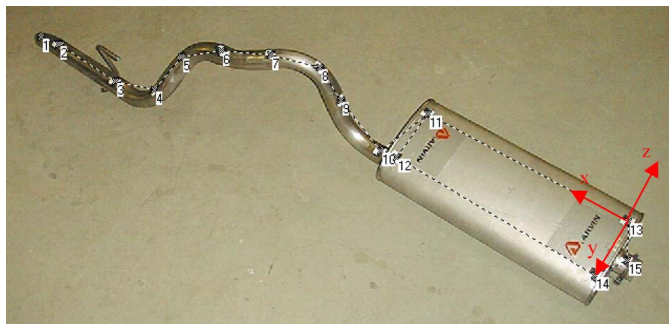

figure 7: measurement object and camera positions

Tests with good positions :
- Test 1 : 3 photos
- Test 2 : 4 photos
- Test 3 : 5 photos

Bad tests :
- Test 4 : 2 photos with angles between the shots close to 90°
- Test 5 : 2 side by side photos
- Test 6 : 3 side by side photos

A comparison between the results of these tests and a conventional high-precision Coordinate Measurement Machine gives the following graphs (figure 8).
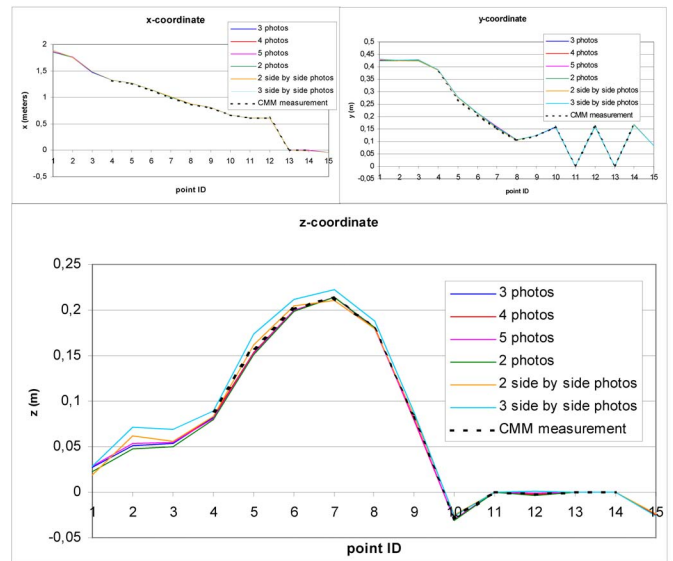

figure 8: coordinates in x,y and z direction for the different tests

The origin is point 13.

The tests with good angular positions give coordinates very close to the CMM measurement even the for the test with only 2 photographs (test 4). Apparently, 2 photos are enough but, in this case, following the photography guidelines is an essential condition.

On the other hand, we can note that the « side by side » tests give worse results. They are proportionally higher than the four other ones.

The following figures give the difference in coordinates w.r.t. to the CMM measurements (figure 9):
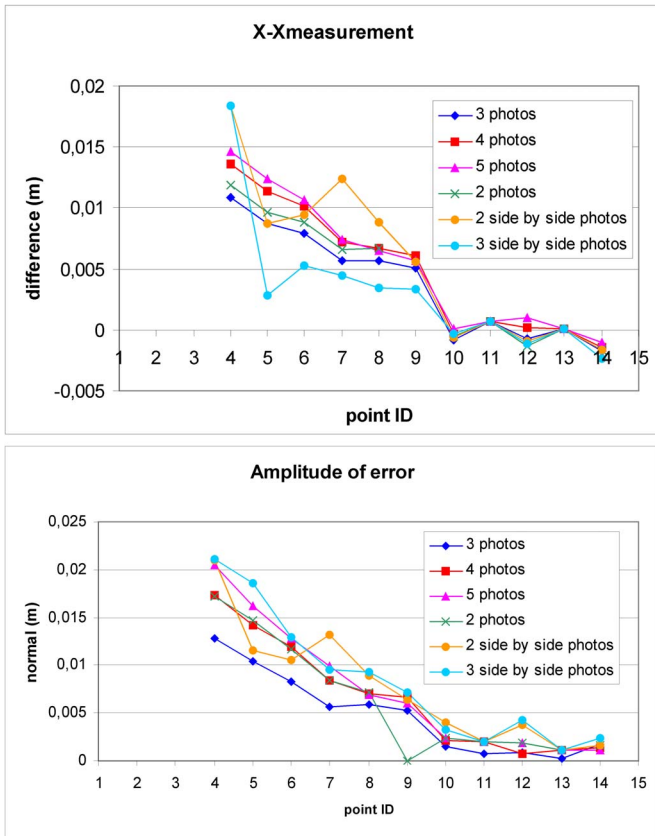
X-Xmeasurement

Amplitude of error

figure 9: difference in x direction and total deviation w.r.t. CMM

The conclusions are similar to those before. The four tests (2, 3, 4, 5 photos with good angles) show the same evolution and they almost give the same differences compared to the CMM results.
The « side by side » tests lead to worse results. This was expected because of the camera positions (side by side).

Points that are far from the origin (point 13) produce an deviation almost proportional to the distance between them and the origin. It is probably due to the fact that the coordinate system of the CMM is slightly different from the photogrammetric one. According to the x, y and z difference graphs, rotations along the x (~0.5°) and the y (~1.5°) axis explain this problem. Therefor it should be pointed out that the numbers shown here should not be interpreted as "errors". The real error is probably smaller than these values.

The conclusion is that the number of photos has few effect on the accuracy of points coordinates but on one conditions: the camera positions have to respect the « 90° » guideline. This experiment also allowed to evaluate the error which can been done if the « 90° » guidelines is not respected. It seems that with a little care a result almost as accurate as those obtained with « good positions » tests can be obtained.

Note : the other points (quality of the calibration, resolution of the camera, precision with which the user marks the features) that may affect the accuracy are obvious. They will not be developed in this report.   It

should also be stressed that the resulting deviations from the CMM measurement

An other test has been realized on the exhaustpipe, measuring 52 points distributed and all sides of the exhaust, with 10 photographs (figures 3 and 4).

The comparison between 3D measurement machine and PhotoModeler gives the following graph:
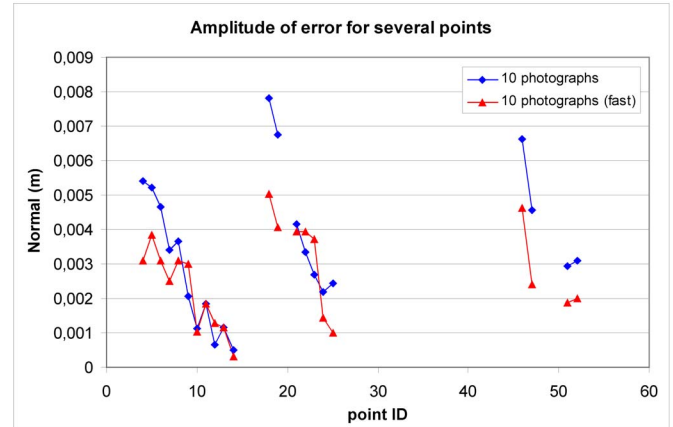

Amplitude of error for several points

figure 9: deviation for 10 picture tests (w.r.t. CMM)

Two tests have been done. They both contain the same 10 photos. The difference between these two tests is that one has been carefully done (marking features was done within one pixel with an important zoom) and the other has been quickly done (without using important zooms).

- Also here, a deviation between the CMM coordinate system and the photogrammetric one is observed and biases the observer "error"
- The accuracy is very good since it does not exceed a few millimeters (8 mm) in this case despite the previous problem of coordinate system rotation. Therefore the accuracy is probably less than 5 millimeters.
- The error difference between the both test is about 2 mm at the most which corresponds to the pixel resolution (1280x780 resolution for a 2 meters structure) for this project. It is quite normal to find this error difference between the fast and the careful test since the precision with which a point can be marked is equal to the pixel resolution.

3. PRACTICAL EVALUATION ON DIFFERENT STRUCTURES

The purpose of this section is to give an evaluation of the total time it requires for an operator with some experience to do the whole process, from point labeling on the structure to a usable geometric model in the modal analysis software. For this purpose it is also important the photogrammetric software not only allows to measure the coordinates of the points that are going to be measured, but gives some additional capabilities which are useful when doing a modal analysis:

- point labeling: it is important to have the capability to label the identified directly in the photogrammetric software. This allows to directly import the results in the modal analysis package, without the need to re-label according to conventions used in the modal laboratory. It also gives additional documentation for final measurement reports: pictures superposed with the 3D model and the point annotation.

- Lines and surfaces: adding lines and surfaces between points is much easier to do with the picture in background, rather than on a "cloud" of 3D points. Typically less errors will be made due to bad connections of points (a typical problem when defining a 3D model in the conventional way in Modal analysis) (figure 13).

- Surface texturing: for modal analysis, only a limited number of points are measured. Therefor the 3D visualization of the model, and its deformation is sometimes difficult to interpret. Adding surfaces will usually enhance the interpretability of the mode shape. A further step could be to render the surfaces with "photorealistic" textures, taken over from the photographs.

The two tests were done with the above mentioned camera and resolution and with PhotoModeler Pro Rev 4b. The resulting 3-D model were imported in the LMS CADA-X Geometry module (Rev 3.5.C) with an interface program allowing to retrieve points with their label (including if necessary a component name), connections and surfaces.

Figure 10 : photographs of the exhaust in different posistion

3.1 EXHAUST:

The exhaust shown in figure 3 and 4 was measured on a total of 52 points, by using 10 photographs. The total time was approx. 2hours. Doing this "by hand" would probably have taken approx. the same time, but with a much worse accuracy, and with less "documentation" of the measurement points.

Photographs were taken with the exhaust in different positions, to verify that even if the object is moved, the 3-D modeling process can still be done without any problem (figure 10, 11 and 12).
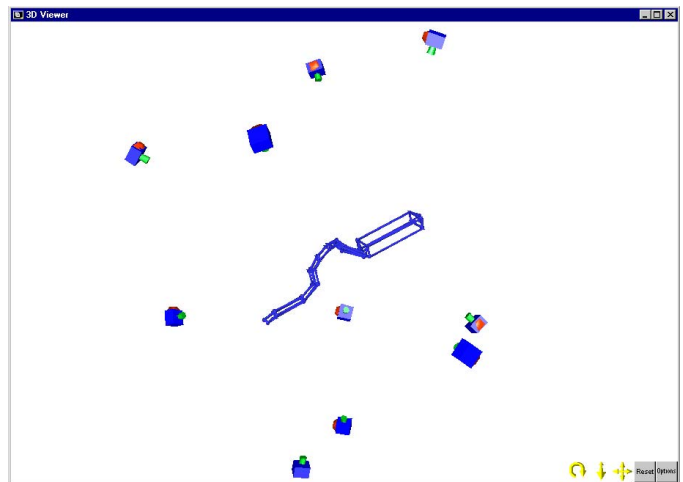

Figure 11 : resulting 3-D model of the exhaust with visualization of the camera positions
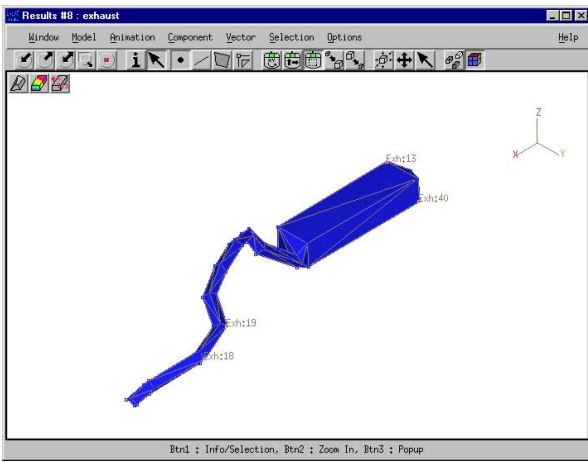
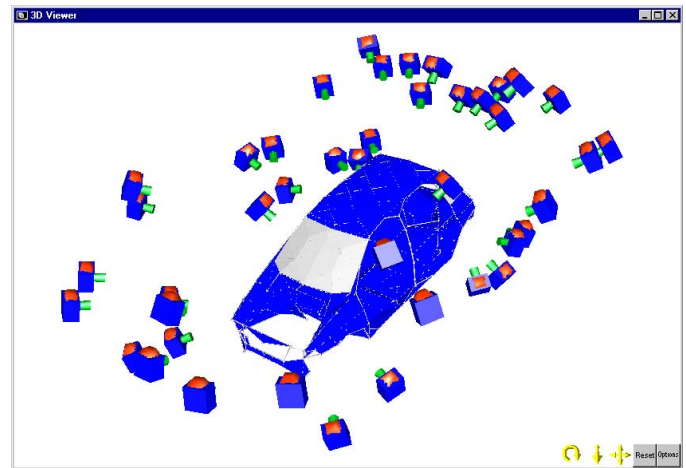Figure 12 : resulting 3-D model imported in LMS CADA-X

Figure 14 : resulting 3-D model of the body in white with visualization of the camera positions

3.1 BODY IN WHITE:

A full body in white was marked with 256 points (including points inside the body and in the engine compartment). 46 photographs were taken. The total time for the whole process was only 5 hours (figure 13 and 14).

Figure 13 : photographs of the body in white with marked points, lables, lines and surfaces (full body and detail of wheel hub)

This test revealed following additional practical information:

- With a sufficient number of photos (judiciously taken), it is always possible to define the required points.
- Shooting of details (wheel hub, inside of the car) is always possible with good overlaps between detail photos and the others (figure 13 – lower).
- Adding points is not a problem. Even if you forgot to mark some points on the structure, adding new photographs with these new points and good overlap is really possible.
- Comparing accuracy with another measurement method was not done in this case. But the important number of points allow to give information about this accuracy: some points are marked on both sides of some panes. They result in a model without interpenetration (the thickness of the metal sheets is found), the car is not apparently deformed, curved surfaces (windscreen, roof, …) are accurately defined, the length and the width of the car are correct according to manual measurements.

As a final test it a geometric correlation with a finite element model of the same car was done, using LMS CAE Gateway. This is usually the first step that needs to be done when doing a correlation analysis of the modal analysis results.
In this case, this geometric correlation was made easy by two factors: 1. the "experimental" geometry model was a lot more accurate than it would have been if it was measured "manually".; 2. Because each measurement point was clearly identified on a photograph too, it was also easier to select 5 good pairs of correlating points, so that an automatic transformation calculation and node pairing could be done. More than 90 % of the testing geometry are correlated with a tolerance lower than 5 centimetres.
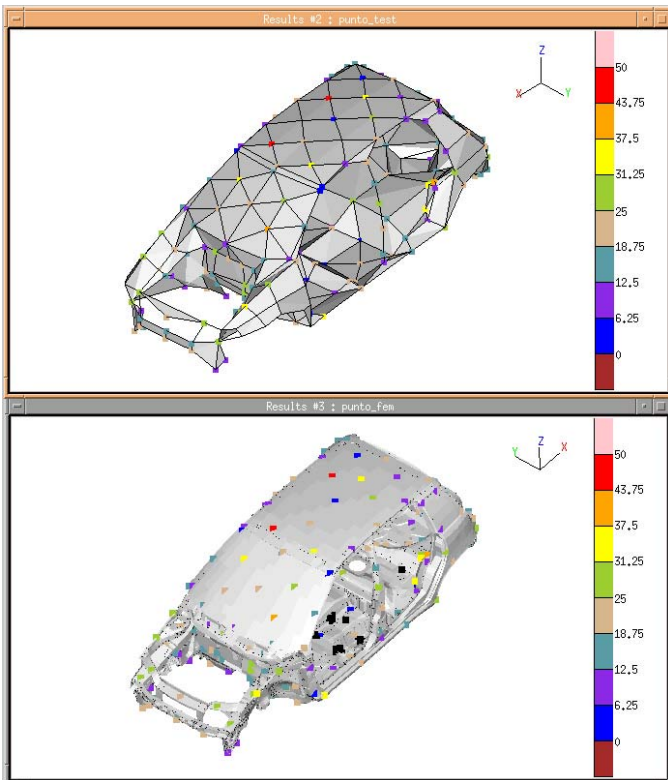
Figure 15 : Correlation result between experimental 3D model and FE model

CONCLUSION

Photogrammetry is a very convenient method to measure a geometry for modal analysis. It has the following advantages :

- More accurate than manual method
- Defining connections and surfaces between points is easier with the help of the photographs
- Easy to use

- The duration of a measurement session is very interesting for the same accuracy
- Possibility to move the studied structure as you want
- Short immobilization time of the structure
- Practical for geometrical correlation between testing and FE models because more accurate
- Documentation for reporting

When handling large project, it is important to work with methodology, in order to master the large amount of photographs.

Higher accuracies can probably be obtained with more professional equipment, or with other digitizing techniques, but usually at a migh higher costs. For modal analysis purposes, a very high accuracy is usually not required, because anyway the transducer will not be place with an accuracy better than approx. 1 mm.

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