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Scanner of Dynamic Deflections (SCADD): a new approach for field data acquisition of the vibration of civil structures

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ABSTRACT
We describe a novel instrument for the remote measurement of dynamic deflection shapes of structures several tens of meters long, based on geometrical optics techniques with scanned laser illumination, which we have named Scanner of Dynamic Deflections (SCADD). A set of aligned control points is measured in each scan, each point being defined by a retroreflector attached to the structure. By measuring the delay of the optical signal reflected from each point, the system renders a component of the displacement of that point which is transverse to the illumination direction.

The intended application of SCADD is the field data acquisition for diagnosing the structural health of civil infrastructures, either as a stand-alone instrument or integrated in a non-destructive structure testing system comprising several data sources, typically an array of accelerometers and a SCADD unit. The foreseen measurement accuracy and the spatial and temporal sampling density of SCADD are adequate to the application of modal analysis techniques.

For the purpose of locating our proposal in its technological context, we include firstly a brief description of the most usual methods (optical and non-optical) for the field measurement of vibrations of civil structures. Then, the SCADD principle of measurement and architecture are detailed. In the experimental section we describe a SCADD prototype and a series of measurements of a control point located 18 m away from the SCADD head, from which we extract the repeatability and a calibration curve of the prototype. Finally, the main advantages of SCADD are detailed.

Keywords: Dynamic Deflection Shapes, Laser Scanning, Structural Health Monitoring, Dynamic System Characteristics, Modal Analysis.

1. INTRODUCTION
Structural health monitoring (SHM) of bridges, buildings and other constructions is a subject of increasing importance in developed countries. Although there are available different methods of proven efficacy and widespread use in this engineering area, new methods are demanded that allow a simpler and cheaper operation, avoiding the installation of ancillary reference structures or the deployment of large cable networks to interconnect the transducers with the signal processing units.

Exploiting the intrinsic advantages of the optical methods for making fast and remote measurements, we have contrived a novel instrument for field data acquisition of dynamic deflection shapes of civil structures, the SCADD, whose presentation and description is the object of the present work.

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2. FIELD DATA ACQUISITION OF VIBRATIONS OF CIVIL STRUCTURES

2.1 Non-optical technologies

The methods based on the measurement of static or dynamic displacements of selected points of the structure by contact transducers (LVDT and similars) present strong limitations, mainly the need of a reliable reference frame to attach the transducers. The methods based on accelerometers, inclinometers or other self-referenced sensors avoid the aforementioned limitation and are more practical for inspecting large structures. By means of an array of sensors working in a synchronized manner, it is possible to acquire information of the dynamic deflection shapes, which allows the application of the powerful modal analysis techniques. In the last years, wireless sensor networks have been a research subject of increasing popularity due to their high potential for SHM. Other contact methods like strain gauges are sensitive to structure deformations instead of displacements.

2.2 Optical technologies

Nowadays there are available in the market many different automatic optical techniques for the measurement of displacements and deformations of generic objects (see, for example, Refs. 4 and 5). Among them, we can highlight some specifically applicable to civil structures:

- Moiré techniques are traditional image (or whole-field) techniques adequate to obtain 2D maps of contours, displacements or deformations by the intermodulation of regular patterns or rulings projected or attached to the structure. In Ref. 8, the measurement of resonant modes and frequencies is reported. More recently, new configurations with very similar principles of operation have been introduced under the denomination of structured light techniques.
- Speckle pattern photography is similar to the moiré technique, with the advantage that the grid is not necessary, being substituted by the speckle pattern originated by the proper object surface irregularities under coherent illumination.
- Interferometric techniques present a high sensitivity (at the nanometer level) but also a high susceptibility to environmental perturbations. They can be implemented in a pointwise scheme (simultaneous measurements of only one point) or as a whole-field method. Interferometric pointwise instruments have been employed for the monitoring of bridges and other large structures.
- Holographic and interferometric speckle techniques allow the application of whole-field interferometric techniques to rough objects. In the same way that interferometric techniques, they are vulnerable to external perturbations and their cost increases dramatically with the size of the tested object, for which they are not adequate for the present application.
- Fibre optic sensors are increasingly employed as an alternative to strain gauges. They are adequate for permanent installation, preferably embedded during the construction stage of the structure.
- Geometrical techniques. Among the variety of possibilities (see, for example, Refs. 7 and 14, the following ones are remarkable:
  a) Multipoint sequential techniques: they perform the sequential interrogation of a set of points by scanning the illumination-detection target. To this class belong techniques like laser alignment, telemetry by triangulation, telemetry by laser scanning and the popular telemetry by time-of-flight.
  b) Image techniques: they perform the simultaneous interrogation of a set of points into the instrument field of view. To this class belong techniques like alignment telescopes, photogrammetry, digital image correlation, theodolites, shadow projection, etc. The image techniques allow a high information acquisition speed because of their acquisition in parallel but, on the other hand, have a lower sampling rate at each individual point when compared to the multipoint sequential techniques. In addition, the need for illuminating power is proportional to the size of the field of view, which supposes a penalty for their application to large structures.
3. A NEW APPROACH: THE SCADD

3.1 Desirable performances of a field data acquisition system for vibrations of civil structures

For the intended application of measuring the dynamic deflection shapes of bridge decks and girders, concrete floors, roofs, etc., the typical distance range is tens of m, the direction of the displacements of interest is, in many cases, the perpendicular to the structure plane and the required accuracy of the order of 0.1 mm. If global monitoring methods (like modal analysis) are employed, to check the whole structure it is not necessary to measure the movement of all its points, but a sampling limited to several tens or, at most, a few hundreds of points is usually enough.

The sampling frequency should be, at least, twice the maximum frequency of the vibrations to measure. A convenient range for typical large structures is 100-300 Hz.

As the system must operate in the field, robustness, simplicity, ease of utilization and economy are also aspects to consider.

3.2 SCADD principle of measurement

Taking into account the criteria exposed in the paragraph 3.1, we discarded the methods based on images due to their limited field of view/resolution ratio, inadequate aspect ratio of the image sensors, slow frame frequency and high required optical power to simultaneously illuminate a large structure. Instead, we explored the possibilities of sequential multipoint methods implemented by scanning a laser beam over an array of control points of the structure. Given the requirements about the size of the structures to inspect and accuracy, we finally selected a geometrical technique belonging to the group of telemetry by laser scanning, and we contrived a novel instrument for the remote measurement of dynamic deflection shapes of structures: the Scanner of Dynamic Deflections (SCADD).

In each scanning cycle, the SCADD interrogates the position of every point of a set of $N$ control points $C_i$, with $i = 1, 2, \ldots, N$, on the structure to inspect (Figs. 1 and 2), approximately aligned about a straight line that we call base line, that we will consider at rest with respect to the Earth reference frame and that defines the $x$ direction. Each control point $C_i$ is defined by a retroreflector $R_i$ conveniently attached to the structure. The laser beam LB is scanned describing a plane, the scanning plane, in such a way that the successive positions of the beam axis diverge from a unique point, the scanning vertex $V$, located near the illumination aperture of the SCADD head SH. In operation, the scanning laser beam illuminates sequentially all the retroreflectors while a detection aperture, located in the SCADD head just beside the illumination one, collects the light scattered by the retroreflectors, SL. The location of the SCADD head is selected to ensure a small value of the angle between the laser beam and the base line for all the control points.

![Figure 1. Geometry of operation of the SCADD system. SH: SCADD head, which contains the emitter-receiver subsystem; FS: frame with suspension subsystem; St: structure to inspect; LB: scanning laser beam; $R_i$: $i$-th retroreflector; SL: light scattered from the retroreflectors; $x$ axis: base line; $V$: scanning vertex.](image)

Although to exploit the metrological limits of the SCADD it is worth taking into account the motion of the SCADD head reference frame with respect to the Earth, to illustrate the principle of measurement it is enough a simplified treatment in which we will suppose that both frames are not in relative motion. We will also suppose that the scanning is fast enough to freeze the motion of the retroreflectors. Provided the instantaneous angular position, $\alpha (t)$, of the scanning beam (referred to a given time base and to a reference frame fixed to the SCADD...
Figure 2. Geometry for the measurement of the position of the $i$-th control point in the $j$-th scanning cycle, $C_{ji}$. $V$: scanning vertex; $O$: origin of coordinates; $OX$: baseline; $h$: height of the scanning vertex; $\alpha_{ji}$: angular position (referred to the SCADD head frame) of $C_{ji}$; LBA: laser beam axis; $R_{ji}$: $i$-th retroreflector in the $j$-th scanning cycle; $x_{ji}$: base distance of the point $C_{ji}$; $z_{ji}$: height of the point $C_{ji}$; $e$: retroreflector height.

Figure 3. Geometry for the measurement of the displacement $u_{ji}$ of the control point $C_{i}$ between the $j$-th and $k$-th scanning cycles.

head) is known, the system renders the instantaneous angular position $\alpha_{ji}$ (referred to the SCADD head frame) of the $i$-th control point in the $j$-th scanning cycle, $C_{ji}$ (Fig. 2), simply by measuring the temporal coordinate (in the aforementioned time base) of the optical pulse coming from the $i$-th retroreflector in the $j$-th scanning cycle, $R_{ji}$. If, in addition, the base distance $x_{ji}$ is known, then the change of angular position between the $j$-th and $k$-th scanning cycles, $\alpha_{ki} - \alpha_{ji}$, gives a direct indication of a component of the displacement $u_{ji}$ of the point $C_{i}$ (referred to the Earth), specifically the component which is perpendicular to the laser beam direction $VC_{ji}$ and contained in the scanning plane $XZ$ (Fig. 3).

Usually, the displacements $u_{ji}$ of the control points have unknown directions, so a unique SCADD unit cannot determine these displacements. Moreover, the base distance $x_{ji}$ is known only approximately because it...
changes due to the structure vibration. However, if the displacements are predominantly out-of-plane, that is, in direction $OZ$, (as is the case, for example, in certain bridge decks and girders), we will show that it is possible to estimate the $z$ component, $u_{zik}$, of the displacement $u_{jk}^i$.

From the geometrical relationships of Fig. 2,

$$z_i^j = h - x_i^j \tan \alpha_i^j$$

expression that, for the $k$-th scanning cycle, is written as

$$z_i^k = h - x_i^k \tan \alpha_i^k$$

The out-of-plane component of the displacement (Fig. 3) is:

$$u_{zik}^{jk} = z_i^k - z_i^j$$

and the in-plane ($x$) component:

$$u_{xik}^{jk} = x_i^k - x_i^j$$

If the displacements are predominantly in direction $OZ$, the angle $\gamma$ is small and $u_{zik}^{jk}$ can be estimated with a reasonable accuracy even being $u_{zik}^{jk}$ unknown. From Fig. 3,

$$v_{zik}^{jk} = x_i^j (\tan \alpha_i^j - \tan \alpha_i^k)$$

$$u_{zik}^{jk} = x_i^j (\tan \alpha_i^j - \tan \alpha_i^k) - (x_i^k - x_i^j) \tan \alpha_i^k = v_{zik}^{jk} - v_{zik}^{jk} \tan \alpha_i^k$$

or

$$u_{zik}^{jk} = k_{uv} v_{zik}^{jk}$$

being

$$k_{uv} = \frac{1}{1 + \tan \gamma \tan \alpha_i^k}$$

where we have introduced the distance $v_{zik}^{jk}$ as the estimate for the out-of-plane component of the displacement. We will refer to $v_{zik}^{jk}$ as the apparent out-of-plane displacement.

The relative error generated when estimating $u_{zik}^{jk}$ by $v_{zik}^{jk}$ is:

$$e_{uv} (u_{zik}^{jk}) = \frac{|u_{zik}^{jk} - v_{zik}^{jk}|}{u_{zik}^{jk}} = \frac{|k_{uv} - 1|}{k_{uv}}$$

For example, if $\gamma = \alpha_i^k = 20^\circ$, then $k_{uv} = 0.88$ and $e_{uv} (u_{zik}^{jk}) = 0.13$, which is a value yet acceptable for the intended application of the SCADD.

### 3.3 SCADD architecture

The SCADD system comprises five subsystems, described in the following paragraphs:

- Emitter-receiver subsystem.
- Retroreflection subsystem.
- Acquisition and treatment subsystem.
- Suspension subsystem.
- Stabilization subsystem.
3.3.1 Emitter-receiver subsystem

This is the main subsystem of the SCADD. It provides the optical signals for sensing the vibration of the structure and transforms them into electrical signals. It is located in the SCADD head SH (Fig. 1) and integrates optical, optomechanical and electronic components (Fig. 4) on a rigid mechanical frame to perform the following functions:

- Laser illumination: the optical power should be adequate to operate over distances of tens of m, even in daylight. To minimize the beam divergence over long propagation distances, a laser source with a single TEM$_{00}$ transversal mode is desirable, along with quality optics (telescope) for beam expansion and focusing. The beam waist location should be selectable, the usual setting being in the zone between the central and the last retroreflectors. The laser head may be located inside the SCADD head or, alternatively, outside it and introduced via a single-mode optical fibre.

- Laser beam scanning: the full angular extent of the scanning is typically smaller than 20 degrees. The scanner optical aperture and output waveform distortion in both macrogeometric and microgeometric (i.e., roughness) domains are critical subjects. The scanning frequency is determined by the dynamics of the structures to inspect and it should be, at least, twice the maximum frequency of the vibrations to measure.

- Internal reference: to improve the accuracy in the instantaneous angular position of the illuminating laser beam, a beam sampled from the scanner output is directed to a reference optical system sensitive to the beam orientation. In our design, this is accomplished by a lens that focuses the sampled beam onto a special optical element, which we name master ruler, with a periodic structure that provides a set of narrow, high contrast optical pulses, each one corresponding to a precise angular position, $\alpha_{rl}$, of the illuminating beam (referred to a reference frame fixed to the SCADD head), being $l = 1, 2, \ldots$, the identifying index of the reference pulse.

- Collecting and, eventually, concentrating or integrating the light scattered by the retroreflectors.
Photodetection in the sensing and reference arms. Typically, two identical amplified photodiodes are employed. The critical parameters are the bandwidth (about 10 MHz), detector area (as large as possible to simplify the collecting optics), and the signal-to-noise ratio of the photodiode-preamplifier system.

3.3.2 Retroreflection subsystem
This subsystem comprises a set of retroreflectors attached to a flexible strip which allows their deployment on the structure to inspect, maintaining the alignment and spacing between retroreflectors.

3.3.3 Acquisition and treatment subsystem
Includes an analogue-to-digital converter with two fast channels (about 100 Msamples/s with 12 bit resolution) for the sensing and reference signals and memory enough to record significant series of vibration data (several GB). In addition, software for data screening and averaging and the user interface must be specifically developed.

3.3.4 Suspension subsystem
This subsystem is necessary to uncouple the SCADD head from the mechanical perturbations generated by the proper structure to inspect, on which the SCADD is intended to rest. Isolation from both translations and rotations must be provided. The degree of isolation depends mainly on the required measurement accuracy and on the characteristics of the perturbation: the power spectrum and the direction/orientation of the structure translations/rotations at the SCADD head location. Basically, there are two alternatives to perform the isolation:

a) Passive, by inertial means (low-pass mechanical filters).

b) Active, by employing actuators controlled by inertial sensors (accelerometers), inclinometers, etc.

3.3.5 Stabilization subsystem
This subsystem complements the suspension one and ensures a precise angular locking of the scanning plane to the line of sensing retroreflectors. A possible solution would be an active system in closed-loop configuration using gyroscopes as actuators and an error signal generated from a special alignment retroreflector intercepting the sensing beam.

4. EXPERIMENT

4.1 SCADD prototype
We have constructed a demonstrative prototype (Fig. 5) that performs only the fundamental functions of the SCADD, whose characteristics are detailed below.

4.1.1 Emitter-receiver subsystem
Illumination:

- Laser type: diode, single-mode polarization maintaining fibre optic delivery.
- Laser wavelength: 659 nm.
- Illumination beam power (after collimation of the fibre optic output): 10 mW.
- Laser beam diameter: 4 mm at the scanning vertex, 10 mm at 18 m from the scanning vertex.

Scanning:

- Scanner type: resonant, oscillating mirror supported by flexures.
- Mirror diameter and flatness: 30 mm, lambda/4.
- Full angular extent of the scanning: 20°.
- Scanning frequency: 148 Hz.

Detection:

- Detector type (two identical elements, for the sensing and reference channels): photoreceiver comprising a PIN photodiode and a preamplifier.
- Detection bandwidth: DC-10 MHz.
- Active area diameter: 3 mm.
- NEP: 6 pW/Hz$^{1/2}$.
- Saturation optical power: 0.18 mW.
4.1.2 Retroreflection subsystem

- Identification of the retroreflectors: two units, that we denominated $R_2$ and $R_3$, were located at a distance of 18.1 m to the scanning vertex. The $R_2$ unit was attached to the stage carriage of a translation stage (0.01 mm resolution) firmly supported by a tripod at rest on the laboratory building floor. The stage orientation was selected to produce translations parallel to the scanning plane and perpendicular to the incident laser beam. The $R_3$ unit was attached to the frame of the translation stage and was used as a fixed reference.

- Retroreflector type: 3M Scotchlite, Diamond series sheet.

- Size of retroreflector $R_2$: rectangular, 3.0 mm in the scanning direction (magnitude of Fig. 2), 23 mm in the direction perpendicular to the scanning plane.

- Size of retroreflector $R_3$: rectangular, 7.0 mm in the scanning direction, 23 mm in the direction perpendicular to the scanning plane.

4.1.3 Acquisition and treatment subsystem

- Digitizer: digital oscilloscope.

- Number of channels: two (sensing and reference).

- Sampling rate: 50 MS/s in each channel.

- Sampling resolution: 8 bit.

4.2 Results and discussion

The data treatment was simple: for both the sensing and reference channels, the centre of each pulse was determined as the central point of its best-fitting Gaussian curve. For the sensing channel, these points are a good estimation of the angular position, $\alpha_i$, of the respective retroreflector centre, $C_i$ (see Fig. 2). For the reference channel, these centres (that we call $REF_i$) mark precise angular positions, $\alpha_{rl}$, of the illuminating beam, which are fixed with respect to the SCADD head.

If the scanning repeatability with respect to time was perfect, it would be convenient to employ the time base of the digitizing process as the standard to which refer the angular coordinate of any pulse (previous calibration of the time base to locate it in the angular scale). However, due to the jitter of the scanner, the calibration table
that converts each temporal coordinate to an angular one is changing from one scanning cycle to the following. In consequence, it is better to determine the angular position of a sensing pulse in a given scanning cycle by measuring its position with respect to the reference pulses of the same cycle, employing the time base only as a link between the reference and sensing channels.

Even employing the described differential procedure, the scanner jitter introduces an error that increases with the time lapse between the sensing pulse and the reference pulse. For example, in our prototype we observed that the standard deviation of a measured angle interval was approximately proportional to the angle interval. To minimize the errors, a high number of reference pulses in each scanning cycle should be used to ensure a short temporal lapse between each sensing pulse and the nearest reference pulse. In our prototype we employed a master rule that generates about 50 pulses per scanning cycle.

Processing the signals from the retroreflectors $R_2$ and $R_3$, we obtained the temporal coordinates of their respective centres, $C_2$ and $C_3$ (the employed units are samples, being one sample equivalent to 20 ns or 3.16 microradians or 0.0572 mm at 18.1 m from the scanning vertex). From the reference channel we obtained the coordinates $REF_l$, with $l = 1, 2, \ldots$, of the centres of the reference pulses.

The jitter of the SCADD prototype was evaluated by measuring a series of 9 differences between $C_3$ and the nearest reference pulse, $REF_5$. The obtained data are represented in Fig. 6, being the standard deviation 1.79 samples, which is equivalent to 5.7 microradians or 0.10 mm. Taking into account that the usual operating mode of the SCADD is differential, each angular displacement measured requires subtracting two angular coordinates, so the jitter in the measurement of an angular displacement will be $2^{1/2}$ times greater, that is, about 8 microradians.

We evaluated also the calibration curve for the tested working point by measuring a series of differences between $C_2$ and the nearest reference pulse, $REF_4$. Each value of $C_2$ is measured only once and afterward the retroreflector $R_2$ is translated 0.10 mm. The process is repeated to obtain 10 values. The obtained data are represented in Fig. 7. The maximum deviation of an individual sample with respect to the regression line is about 4 samples, which is a value similar to that encountered in Fig. 6. The theoretical slope of the calibration curve is -17.5 samples/mm, being the experimental value -24.1 samples/mm. This last value gives a sensitivity of 4.38 microradians/sample instead of the theoretical value of 3.16. The difference is quite high but it must be taken into account that the standard deviation of each measured point is much higher (5.7 microradians), and also that the number of measurements done is small, so both slopes seem compatible with each other. Further measurements should be done to have a more precise understanding of the behaviour of errors.

5. CONCLUSIONS

A novel instrument for field data acquisition of dynamic deflection shapes of civil structures, the SCADD, was presented and experimentally demonstrated with a laboratory prototype. The obtained repeatability and
sensitivity are, in principle, adequate for the application of structural health monitoring methods based on
dynamic system characteristics and, specifically, modal analysis techniques.

The main advantages of the SCADD in comparison with the methods based on tethered monitoring systems
for acquiring vibration data of large structures (like, for example, accelerometer networks) are the following:

− The SCADD operates remotely from one end (or on an intermediate point) of the structure, being only
necessary to attach a retroreflector to each point to be measured of the structure. In many cases, this
operation can be done by unrolling a set of retroreflectors attached to a flexible strip along the structure
section to be inspected. This process is easier and faster than the sensor attachment and the deployment
of the cabling necessary to collect the signals of a tethered sensor network.

− The measured magnitude is directly a displacement, in contrast with accelerometers that are sensitive to
the temporal second derivative of displacements. In consequence, the SCADD is increasingly competitive
as far as the frequencies of interest are lower and can be even utilized to acquire static deflection data.

With respect to more traditional monitoring techniques based on displacement measuring sensors by mechanical
contact (LVDT and similars), the main advantage of SCADD is that the need of a reliable reference frame
to attach the transducers is avoided.

However, the SCADD presents also some drawbacks: the control points must be aligned, the accuracy
strongly decreases with the distance between the SCADD head and the control point, and only one component
of the structure displacements is measured. To overcome these limitations, envisaged future improvements of the
SCADD include some refinements in the design and the combined use of several SCADD units operating from
different locations.

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REFERENCES


