THE NOVEL IMAGE-BASED TRACKING LASER DOPPLER VIBROMETER

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ABSTRACT
An innovative version of the Tracking Laser Doppler vibrometer based on image acquisition and processing (iTLDV) is proposed. The iTLDV is developed for tracking of arbitrary motions; the system is feed-back controlled and allows to measure vibrations of moving target by driving the moving mirrors via position signals of the target obtained from a CCD camera and an image processing algorithm. The tracking system developed has been applied to an industrial test case subject to self-excited vibrations, in order to verify performances and limits in operating conditions. The system demonstrates its ability to measure vibration time histories on a windscreen wiper in operative conditions. This test case represents a challenging measurement problem, not being available other measurement techniques able to extract such data. Some examples of obtained data are shown, which highlight the potential of iTLDV. In addition, position accuracy and measurement uncertainty is discussed. For the windscreen wiper, the worst position accuracy is estimate as ±1.2 mm along the wiper axis, while the measurement uncertainty is mainly depending on the commercial vibrometer applied in the set-up (about ±2% depending on operative conditions).

1. INTRODUCTION
In several applications it is interesting to analyse the vibrational behaviour of a structure under operative conditions. Frequently, in fact, the constraint conditions, the excitation forces and the stiffness itself can be depending on the real working conditions, and therefore traditional modal analysis techniques, performed with steady object and non-operative excitation, can offer just a partial view of the problem.
A good example of that are moving structures. The motion can determine interaction really difficult to be predicted or to be reproduced in non-moving conditions, such as aerodynamic forces, contact forces and inertial loads. In these cases, it would be desirable to have a Lagrangian observer, so to measure time histories of the vibration of some points fixed to the coordinate system of the moving object.
In several cases contact sensors, such as accelerometers, have demonstrated large limits. In fact, the mass load effect and the geometrical dimensions are not compatible with the application at higher frequencies or on light and small structure, which in addition are also the most sensitive to operative conditions. Furthermore, the installation of a sensor on moving structures, always poses problems of signal transmission from moving to static reference frame (cables, telemetry etc), thus making the set-up complex and invasive, and, on some moving objects, such as belts or window wipers or tires, installation of a sensor is not possible at all.
Full field techniques (as holography and ESPI) do not offer the capability to obtain vibration time history and suffer in case of large target displacement. On the other hands, vibration measurements by ultra-fast image acquisition and processing present typical limits of sensitivity and resolution of any displacement sensor, because amplitude of structural oscillations are very small when the frequency rises. For these reasons the Tracking Laser Doppler Vibrometer (TLDV) was developed [1] [2]. This system allows to follow and to track the movement of the analysed object with the measuring beam of a LDV, which measures vibration in the moving reference frame. In previous works the technique for the measurement of rotating object was described and analysed. Some possible automotive applications and some advances in signal processing were highlighted [3] [4]. In all these cases, target trajectory was known to depend on the position of some member of the mechanism: that position
was measured by position sensors such as encoders. No real feedback was inserted in the system, and tracking was based on a kinematic model of target trajectory.

In this work a novel approach to tracking is shown, in which the tracking feedback is obtained by processing the image of the target on the analysed object. This is an innovative concept in vibration measurement, and it adds flexibility to the application and allows to measure on moving objects even when target point trajectory is not a known function of some measurable parameter. The technique is discussed and an example of application is shown.

2. SYSTEM DESIGN

The image based tracking system (iTLDV) is the natural evolution of previously presented TLDV systems [1] [3] [4]. In this new approach, some limitations of the encoder-based methods are surpassed. Particular features of this innovation are:

1. The a-priori knowledge of the trajectory of the target is not required. In previous TLDV systems, based on an open-loop control, the position sensors (e.g. the encoder) localise the target along the curvilinear coordinate of the trajectory by means of knowledge of the mechanism kinematic model. The application of a closed-loop approach based on image tracking of the target point extends the application to arbitrary motions. Complex modelling of the target trajectory in the SLDV reference frame is then no more required.

2. No alignment problems. Misalignment does not affect the accuracy of tracking, while it is fundamental in classic TLDV. Of course an accurate alignment in any case could simplify the understanding and processing of the data, by reducing the amount of disturbances and of pseudo-vibration signal, but does not affect the tracking error.

3. Any 2D-3D target trajectory is allowed, even if 3D motion may produce disturbances to the signal, due to limited depth of field of the vibrometer.

4. Easy and fast set-up. The set-up becomes easier than the traditional laser Vibrometry. It is sufficient to apply a small white spot on the target point, move the beam close to such point and the system will reach the target automatically, and then track its motion.

The iTLDV system is basically composed by a Scanning Laser Doppler Vibrometer (SLDV) in which laser-scanning mirrors are properly controlled in order to obtain the tracking of a point on arbitrarily moving objects. Two scanning mirrors are the actuators of a closed loop control system, as shown in Figure 1. An image sensor able to observe the instantaneous position of the target with respect to that of the laser is used as feedback sensor, and a controller determines the control voltages to drive the actuating mirrors. While the target object moves the control system corrects the position of the laser beam using the controller’s set-point and the information coming from the camera, which observes the moving object.

In Order to act as feedback sensor, the imaging system should have the same optical axis of the LDV system, so that parallax errors are cancelled out. Therefore the optical lay-out is designed as in Figure 2, with a laser line dielectric mirror which allows the two optical systems to be aligned on the same axis and to observe the target through the same scanning mirrors. Laser line dielectric mirrors are designed for high reflectance at individual laser wavelengths. For a proper camera alignment we have designed the system with the mirror at 45° with respect to the LDV optical axis and to the camera optical axis.

This system will always keep the laser vibrometer axis at the image centre. The camera will receive an image, which will not contain the wavelength of the laser line (λ=632.8 nm) and the narrow band around it (λ=620÷647 nm). Therefore the camera does not image the laser spot. Therefore camera alignment poses difficulties, which can be faced if the camera is mounted on a 6 axis degree of freedom micro-positioning system and if the laser position on the target is identified by a spot of different wavelength, so that it can be imaged during camera alignment.

After alignment, the actual laser spot image would sit at the centre of the CCD. In order to avoid interferences between the target image and the laser spot of the vibrometer and then to improve the target contrast in the image used for in the position evaluation, a green-coloured optical filters is inserted on the camera objective. In Figure 3 an example of the scenario observed by the camera is shown: the image is taken when a tracking error is present. The laser spot, even if filtered out in the real case, was drawn in the picture in its real position (the image centre) and with typical dimension for demonstration purposes. The dimension of this picture, and then the value of the position error used in the control loop, of course depends by the magnification ratio of the optical set-up. From the image in Figure 3, the x and y coordinates of the centroid of
the target point with respect to a reference system having origin in the central point of the CCD image provide the estimate of the $x$ and $y$ scanning error.

3. THE CASE STUDY

In order to demonstrate and analyse the performances of the developed technique a vibration test on a windscreen wiper was performed. Such a case is an example of those problems in which a rather small, flexible and light component is moving along large trajectories, which cannot be accurately reconstructed or modelled. The vibration pattern strongly depends on motion and on interaction with the windscreen itself. The wiper represents an interesting test for the tracking system because of the large accelerations, because the system has large deformations which do not allow to use of tracking LDV based on an encoder on the shaft and because the effects of the contact between the rubber and the glass generate typical vibrations that are important for vibro-acoustic optimisation and need to be measured in operating conditions.

The windscreen wiper used here presents an innovative design: it is composed by a simple iron structure (basically just a elastic cantilever beam), which support the rubber blade and a large rubber spoiler. The rubber blade is 500 x 3 mm with a thickness of about 1 mm. The maximum tangential velocity of the blade tip is typically of about 0.7 ms$^{-1}$.

The frequency bandwidth of interest is 2 kHz, even if the most interesting phenomena are typically in the range of 100 Hz.

The test was performed in two benches designed for this purpose. The first is composed by a simple wiper operating on a flat glass, as shown in Figure 4.

The vibration conditions can be changed through the variation of the load given by the springs, changing the cleaning fluid on the glass and controlling the velocity of the wiper arm.

The out-of-plane vibrations were analysed during some runs of the wiper. Vibration measurements were also acquired by an accelerometer, for comparison. In order to measure at the same location, the laser was tracking the accelerometer casing. Of course in the real application the accelerometer must be eliminated, because it is invasive.

The second bench is composed by a windscreen wiper with a more complicated kinematic mechanism (a four link mechanism) and working on a real curved windscreen, as shown in Figure 5.

In this second case the in-plane vibrations of the rubber blade must be analysed. These components of the vibration pattern, parallel to the screen, are really important to understand the mechanisms of production of acoustic noise at the interface between the rubber and the glass at the changing of constraint conditions, such as the moisture and the temperature.

This is an example of practical application on a moving object in which the load of a sensor determines too high intrusivity and the measurement is not possible with traditional systems, therefore no comparison is possible and the measurements by iTLDV are absolutely unique and original.

One of the major problems in performing the tracking, in particular in the case of in-plane measurement on a point at few millimetres from the windscreen, was the illumination. It is necessary to achieve the correct illumination required for the camera in order to have a high contrast between the target and the surrounding background during the entire tracking phase.

Contrast has been enhanced by the following actions:

a) a dark panel is put behind the windscreen, so to have a uniform and dark background;

b) the rubber blade is painted in black so to reduce the quantity of scattered light which contributes to optical noise;

c) the target point is identified with a circular piece of retro-reflective tape, which maximizes its scattering power in all directions.

The residual problem, and unfortunately the most difficult to be solved, is the reflection of light at the screen surface. It is in fact not possible to modify the optical characteristics of the glass surface without modifying the contact forces between blade and windscreen. In addition the complex shape of real screens will change the reflection conditions point-by-point. The problem can be partly faced by proper positioning of the light source with respect to the glass windscreen and to the iTLDV optical axis, so to minimize noise from reflected light. Finally, the image acquired by the camera can be also processed in order to increase signal to noise ratio (SNR).

4. RESULTS

The tests presented here have the objective to demonstrate the potential of the iTLDV technique in the measurement of operative vibration of windscreen wipers. This is of interest in order to study how temperature, moisture and cleaning fluid can affect the noise produced by the wiper.
5.1. Measurement of out-of-plane vibrations
As previously discussed a first test was performed to analyse the out-of-plane vibration of the wiper (i.e. the velocity of the windscreen wiper in the direction orthogonal to the glass). In order to test the iTLDV an accelerometer was glued on the wiper structure and the laser beam measures on it. The mass of the accelerometer is considered as a part of the analysed structure, for comparison purposes. Figure 6 shows the good agreement between accelerometer and vibrometer signal, taking into account the differences between an absolute pick-up and a relative sensor. For comparison purpose, the accelerometer signal is integrated to have vibration velocity. The laser vibrometer signal shows high frequency oscillations superimposed to a pedestal.

In fact the movement of the wiper determines a continuous change of the distance between the interferometer and the target point. This change is due only to the kinematics of the scanning system with respect to the vibrometer reference frame, so that a relative velocity component is caused by the motion of the wiper. This does not happen with the accelerometer, which is an absolute measuring device.

Analysing the raw data shown in Figure 6 it is possible to extract and eliminate the rigid motion velocity from the vibration signal and to obtain the time history shown in Figure 7. Solid body motions happen at much lower frequency than the blade vibrations, therefore filtering separates the two. The low frequency component allows also to reconstruct the 3-D trajectory of the target point in the vibrometer reference frame.

As it is possible to note there is a good agreement between the two measurements. Some differences appear in particular at the extremes of the time history, where the tumbling of the wiper occur corresponding to the inversion of the motion direction.

Probably these differences are due to the “dimension” of the sensitive elements: in the Doppler system the measure is performed in a very small spot (about 0.1 mm), instead of in the accelerometer that present a “sensitive area” about hundred time larger. For this reason, the vibrometer can see also the rotational degree-of-freedom of the vibration, that are neglected by the accelerometer, in which the axis of rotation pass thought the large sensitive area. The lever effect due to rotation of the accelerometer amplifies velocity measured by the iTLDV focused on the accelerometer housing.

5.1. Measurement of in-plane vibrations
The second test is presented as the typical application for which the iTLDV has been conceived. The measurement of the vibration time history of the rubber blade of a wiper in in-plane direction (i.e. the velocity of the windscreen wiper in the direction parallel to the glass) is a very difficult task, practically impossible with other techniques. In Figure 8 the scheme of the measurement set-up is shown.

As in traditional SLDV, each acquisition is triggered in order to obtain repeatable results, from cycle to cycle. The trigger pulse was obtained from an optical sensor observing a reference point on the wiper arm: it gives a trigger signal necessary to synchronize the acquisition when the arm is always at a reference angle. The trigger is activated only during clockwise wiper motion. A reference signal to be used for vibration analysis is obtained with an accelerometer applied on the screen and therefore it observes the vibrations induced on the glass by the rubber contact. In this case the reference is used to obtain a phase reference for the acquisition in a grid of points, for monitoring the experiment and to calculate the Transfer Function between the rubber and the screen (in the same way of traditional measurement technique, such as accelerometer or SLDV). This transfer function is interesting for manufacturers of wipers, which are interested in the squeal phenomenon, which is a typical unwanted vibration of the wiper-screen system.

In Figure 9 an example of result, acquired in squealing and non-squealing conditions, is shown. It is possible to observe:
1) the pedestal on the signal due to the rigid motion. This is a low frequency, highly repeatable signal that can be filtered as already discussed. In combination with the information of the actual mirror position it allows to obtain information about the trajectory of the target;
2) the low frequency damped oscillation at the start of the motion. Such vibrations are excited by the motion inversion of the wiper.
3) The high frequency vibration (the squealing) at the end of the run. During the squealing the friction forces excite different frequencies. Such vibration grows in amplitude up to a maximum, then it decrease and stops before motion inversion. The ambient conditions affect contact forces, which may be varied so to excite squeal or not.
4) The tracking drop-out. At the end of the run the target point is hidden by the wiper itself and the tracking is stopped.
5. PERFORMANCE ANALYSIS
6.1. Tracking accuracy

The CCD observes a small area, around the target point, which moves with the scanning mirrors depending on the object movement. Image magnification, image resolution and frame rate affect tracking performances. System’s dynamic performances are directly related to the camera’s speed: the higher is the frame rate, the higher is the maximum velocity of the object that the system can track. Due to technical limitations, high-speed cameras have low resolution so just only an area with small dimension can be acquired if a good spatial resolution is needed.

This represents the most important compromise in the choice of system parameters: in fact both the speed and the resolution affect the tracking accuracy.

Generally speaking, the resolution (in terms of image pixels) and the field of view (working with a zoom objective) must be optimised in function of the actual frame rate, the target speed and also of the target acceleration, if some interframe predictor-corrector algorithm is applied.

In synthesis, the position error, in terms of the x and y distances of the measuring point with respect to actual target position, depends on (see Figure 10):

1. Hardware components characteristics:
   i. camera frame rate, i.e. the frequency in position determination. With the applied camera (220 fps) the position error is about 4.5 mm for each m/s of target velocity.
   ii. camera resolution: the increase allows a more accurate position sensing, but the increased image size can saturate the bandwidth of camera data bus and frame grabber at given frame rate.
   iii. computing speed. Actual computers do not represent a problem for usual tracking algorithms. Interrupts of not Real-time Operative Systems can cause unexpected delay.

2. Control:
   i. control algorithm (PID, predictor, etc)
   ii. control parameters

3. Environmental factors, that, in practice, play a fundamental role:
   i. electromagnetic noise: It can determine uncontrolled mirror vibrations and drop-outs.
   ii. optical noise: the target can disappears for a not accurate illumination or some false target points can appears if reflections or bright spots enter in the field of view of the camera, making necessary the application of image processing algorithms to eliminate this effect, as already discussed.

4. Target motion:
   i. velocity
   ii. acceleration, if predictor schemes are applied.

A first order model can be used to estimate tracking errors $\Delta x$ and $\Delta y$ in the object plane; $x$ and $y$ directions are referred to the image coordinate system and each one depend on one single actuator.

For each direction we can write

$$\Delta x = v_x \left[ \frac{1}{fps} + t_{data\_transfer} + t_{CPU} + v_x \left( \frac{1}{fps} \right) \cdot \frac{1}{d \cdot \Delta \theta_{max} \cdot f_{max}} \right]$$

if $t_{CPU} \leq \frac{1}{fps}$

where

$\Delta x$ is the position error
$v_x$ is the target velocity
$fps$ is the camera frame rate
$t_{CPU}$ is the CPU time for image processing and PID algorithm calculation
$t_{data\_transfer}$ is the time for data transfer from the frame grabber to the CPU
$d$ is the distance between the scanning mirrors and the laser
$\Delta \theta_{max}$ is the scanning system aperture
$f_{max}$ is the maximum frequency of the scanning system
The basic hypothesis is that the time consumption $t_{CPU}$ for image processing and PID algorithm calculation is lower than the time interval between two images, so that the CPU can be ready to process every incoming image. If the processing time does not satisfy this hypothesis it is not possible to exploit completely the performances of the camera.

The fourth contribution is due to the mirrors actuation. It is a simplified expression that depends on:
1. the frequency response of the scanners;
2. the geometrical amplification of beam velocity due to the distance between the scanning mirrors and the laser;
3. the distance covered by the target between two consecutive images.

State of the art technology shows that the frame rate is the bottleneck of the system and all other delays can be neglected in the proposed system. In fact, the hypothesis on the processing time is easily satisfied with recent CPUs that allow to obtain really short calculation time (of about some microseconds), also because of the simple and fast control algorithm applied and thanks to the implementation of all pre-processing image functions on the frame grabber. Finally, the delay of the actuators is not critical in the discussed application. In fact, the geometrical arrangement allows to move the beam at the desired velocity with a small angular velocity of the mirrors, being $d$ large. In choosing the distance it is necessary also to find a compromise between the laser beam speed and the position resolution, which depends on $d$ for given angular resolution.

With reference to the test described in Paragraph 5.2, which represents the most relevant application of iTLDV, the typical transversal velocity (i.e. in the direction orthogonal to the vibrometer axis) of the measured points on the windscreen wiper is lower than 0.3 ms$^{-1}$ in the x direction, while in the y direction the movement is only due to the screen shape (it is virtually zero in flat screen): x and y are referred to the image plane. The comparison between the position error, the object dimensions and the wavelength of the vibration allows to define velocity limits of the motion for a given tracking set-up. The maximum position error in this application turns out to be $\pm 1.2$ mm in the x direction and $\pm 0.1$ mm (i.e. of the same order of magnitude of the laser spot) in the y direction, in any case much lower than the wavelength of the vibration in the medium (which is higher than 2.25 m for the iron support and than 0.8 m for the rubber blade, being the analysed frequencies lower than 2 kHz).

6. CONCLUDING REMARKS
Image Tracking Laser Doppler system (iTLDV) has been developed for vibration tests on arbitrarily moving objects. It is an innovative and original approach to TLDV. This technique does not require position transducers connected to the measuring structure, because all the information needed for tracking are obtained by image analysis. For these reasons the proposed technique keeps the advantages of traditional laser Doppler Vibrometry, and adds the ability to work on moving objects, providing a versatile measurement system. With respect to the previous version of TLDV, the use of images in order to close the control loop allows to obtain a fully non-contact measurement system, able to measure on arbitrarily moving objects. Windscreen wipers were chosen as test cases because they highlight the limits of traditional techniques. In particular on the wiper rubber it is practically impossible to apply any kind of contact sensor. In fact any mass load is not acceptable and the contact with the windscreen makes it difficult the installation. The Tracking capability allows to exploit the performances of a laser vibrometer even when a large movement is present, subtracting its effects by signal processing. The position accuracy is smaller then the typical accelerometer size and of wavelengths of interest in the presented test case, and the tracking add-on do not affect significantly the uncertainty of the velocity measurement. The bandwidth of the complete set-up is just depending by the commercial vibrometer employed.

8. ACKNOWLEDGEMENTS
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Figure 1. Closed-loop control scheme.

Figure 2. Layout of Scanning Laser Vibrometer.

Figure 3. Example of instantaneous image of feedback loop.

Figure 4. The simple windscreen wiper on the flat glass.

Figure 5. The complex wiper on a real windscreen (Courtesy of R. Bosch Gmbh).

Figure 6. Vibration time histories obtained on windscreen wiper.

a) Vibrometer signal time history.

b) Accelerometer signal time history.
Figure 7. Comparison between the time histories obtained on windscreen wiper.

Figure 8. In-plane vibration time history of the wiper rubber:
a) Without the squealing; b) With the squealing

9. REFERENCES