

Non-Contact and Real-Time Displacement Measurement System for Structural Health Monitoring

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Abstract

In this paper, a multi-channel high-rate laser displacement sensor system accompanied with an open-source data acquisition software for structural health monitoring was explained. Hardware part of the system composed of three laser triangulation sensors with a resolution of 0.1 mm and a measurement acquisition rate at 70 Hz each. The software part is developed under Python open-source environment and handles initiation of data acquisition, data synchronization and data logging. The developed system was tested for reliability using a free vibration of a three-story model with a set of shaking-table tests and results are presented.

1. Introduction

Structural health monitoring (SHM) has been studied in many fields such as aerospace, mechanics, and civil engineering to assess the condition or state of structures. SHM is the observation of a quantity of a structure for risk detection. The observation period depends on the purpose of monitoring, such as, long-term observations are preferred for determination of landscape shifts and aging effects whereas short-term observations are more suitable for forced vibration effects (such as earthquakes, wind and etc.) on the structure. Research activities in this area is reviewed by Kim et al. [1] including piezoelectric sensors, optical fiber sensors, wireless smart sensors, and vision-based sensing systems. The SHM community uses the data measured directly from a structural system for diagnostic purposes. In such an approach, a number of sensors are deployed on the structure. This type of approach is referred as a direct SHM. In contrast, the use of data not recorded directly from a real structure is referred to as an indirect SHM approach [2]. Investigating effects before the field, forced vibration tests have to be achieved on the small-scaled structures by using earthquake simulators, shaking-tables or etc. To determine the characteristics or damage of the structure, one or several parameters, such as relative displacement, the inter-story drift, velocity, vibration frequency, damping, tilt have to be measured via suitable sensors. Damage detection methods can be generally classified as one of two types: local-based or global-based damage detection methods. Local-based damage detection methods attempt to identify damage based on screening structures at their component or subcomponent length-scales (e.g. cracks, yielding). Global-

based damage detection refers to numerical methods that consider the global vibration characteristics (e.g. mode shapes, natural frequencies) of a structure to identify damage [3]. For measurement of global-based damage detection, traditional method is to use accelerometers [4], GNSS [5, 6] or displacement sensors such as potentiometric (LPDTs) or inductive displacement sensors (LVDTs), however, they require a solid contact with the structure. Today, digital camera based direct displacement measurement approaches have been also proposed to overcome the disadvantages of contact based measurements [7-9]. Laser displacement sensors (LDSs) are much more expensive than LVDTs, but provide contactless measurement which may be necessary especially for light structures and precise damping evaluations. Variety of LDSs models, and manufacturers like Micro-Epsilon® [10], Keyence® [11], Leuze® [12] are available in the market depending on the resolution, range, and accuracy. However, these manufacturers make researchers compelled to use a specific software, especially for one-sensor, that cannot be integrated with another measurement system or not freely customizable. In this work, three laser displacement sensors accompanied with a hardware and open-source software for indirect structural health monitoring. Software is developed in Python open-source environment and handles initiation of real-time data acquisition, data synchronization and data logging. Synchronization and reliability is tested using a free vibration of a three-story structure model with shaking-table tests.

2. System Components

For specify the type of laser displacement sensors the displacement limits, measurement rate and structure's surface properties have to be clarified. For long-ranges (>2 m) Time-of-Flight (ToF) type sensors is suitable with relatively lower measurement rates. In this type of sensor the distance of an object is determined via the propagation time of a light pulse emitted by sensor's transmitter that is reflected by the object and received by the sensor's receiver. ToF type sensor is suitable for large operating ranges with simultaneous immunity to light interference and a low influence of gloss and structures on the measurements value. For medium ranges (<60 mm) Triangulation type sensors should be used. In triangulation procedure the distance of an object is determined via the angle of incidence of the light reflected by the object. For the actual measurement a linear CMOS array is used. This type of sensor permits a fast measurement rate and high accuracy [12]. In Fig.1

triangulation method is briefly described. A laser hits the target, light reflected off of the target is concentrated through the receiving lens and is focused onto the light receiving element. If the distance from the sensor to the target changes (1) to (2), the angle of the reflected light changes causing the position of the received light to change on the light receiving element. This change is proportional to the movement amount of the target, because the distance between each position on the light receiving element is known.

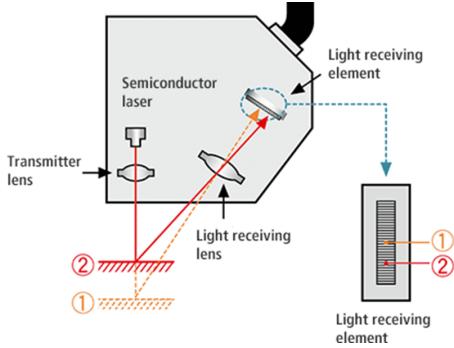


Fig. 1. Measuring principle of triangulation type sensors [11]

In our system three pieces of triangulation type laser displacement sensors from Leuze Electronic GmbH is used. Characteristics and properties of sensor are listed in Table 1.

Table 1. Properties of Laser Displacement Sensor

Model	ODSL 96BM D2 6.S-800-S12
Light source	Laser, Red
Light spot size	1 mm
Measurement range	150 ... 800 mm
Geometric resolution	0.1 ... 0.8 mm
Measuring accuracy	1.5 %
Repeatability	0.5 %
Measurement time	1 ... 5 ms
Black/white behavior	1 %
Supply voltage	18 ... 30 V, DC
Data Output	RS-232

Dimensions and photograph of the laser displacement sensor that is used in this study, is given Fig. 2.



Fig. 2. Dimensions of ODSL96BM laser sensor

Laser displacement sensor requires a special adapter (UPG10) to operate and run the special software of the producer. However, without this adapter, it's possible to get measurement data from

RS-232 line directly as our sensor optionally supports digital output. To connect 3 sensors to PC via one cable, a surge protected USB to 4 Port RS232 converter board is used and all sensor connection is established via USB port of the PC. To remotely control sensors on/off time from PC, a SPST relay is connected to system.

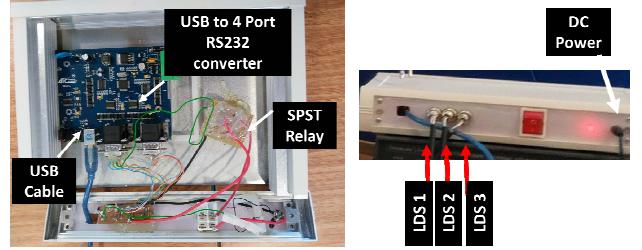


Fig. 3. Hardware part of the measurement system

According to the sensor manual user can set 4 different measurement modes (Table 2). The effect of measurement behavior of the sensor depends on the device [12].

Table 2. Effects of the individual parameters on the measurement function

	Accuracy	Measurement time/updating	Ambient Light	Varying diffuse reflection
Standard	+	+	+	+
Precision	++	--	+	+
Speed	-	++	+	+
Light Suppression	+	--	++	o

For transmission of the measurement values sensor is configured to ASCII transmission mode. In this mode transmission format is;

MMMMM<CR>

where MMMMM is 5-digit measurement value in 0.1 mm and <CR> is the ASCII character “Carriage Return” (0x0D). For instance, if the object is 32.53 cm away from sensor, measurement value output will be 03253<CR>. But if, the distance is out of range, measurement value output is always 65535. The data transmission rate of the sensor is settled to 57600 baud. Serial transmission is performed with 1 start bit, 8 data bits and 1 stop bit without parity. So, with 57600 baud, sending one measurement data nearly takes 1 ms. For our system that includes 3 sensors, each of the sensor data must be separately read without missing any data. As a result of the primary comparison tests we can say that measurement time is not constant and shows variation from one sample to another, even laser beams reflect at same surfaces. This phenomena is a big problem for data logging because data from each laser displacement sensor is coming at different rates and is not synchronized with each other. To overcome this problem a software is developed under Python® (version 2.7.6) open-source environment. Through the development of software, all data reading was realized using multithreaded programming. For

each sensor, time duration of measurement cycle is calculated for each reading. All measurement data is recorded according to the reference time which is the start of measurement. For each sensor, each measurement data is recorded with information reading time durations into separate text files as given in Fig. 4.

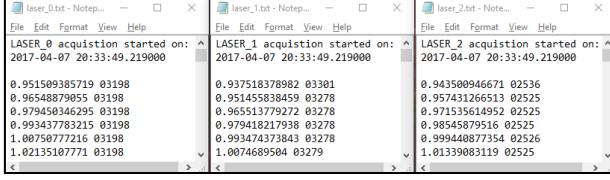


Fig. 4. Simultaneously recorded measurement text data files

3. Experiments

For testing reliability of system an experimental setup was established that includes shaking-table, three-story multi-frame building model, 3 laser displacement sensors and a reference steel frame which provides fixing of sensors (Fig. 5).

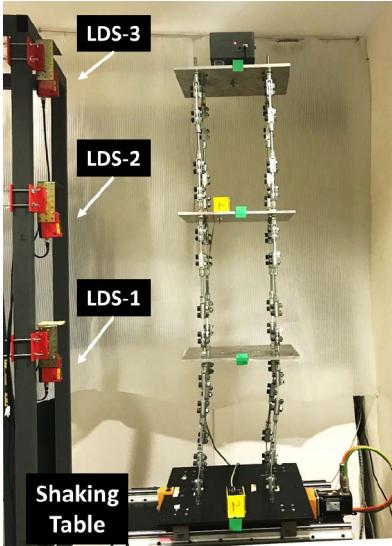


Fig. 5. Experimental setup

Servo-electro-mechanic shaking-table has a single-axis movement with an upper-table size of 50 cm x 50 cm x 1 cm and maximum displacement of +/- 10 cm. It can simulate earthquakes and defined waves such as sine, triangle, etc. or can apply any acceleration or position profile that is user defined [13].

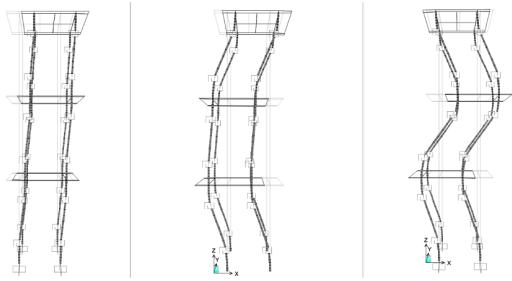


Fig. 6. Estimated free vibration modes of model

Three-story building model is constructed in size of 45 cm x 35 cm x 150 cm. Columns and connection jaws of building was made of steel. Intermediate floors are aluminum with a thickness of 1 cm. Deformation slabs are 5 mm thick aluminum plates and behave like plastic deforming members that can only change their shape in movement direction. From the SAP2000® model of the construction, mode-shapes (Fig. 6) and natural frequencies are estimated (Table-3).

Table 3. Estimated vibration modes and frequencies of model

Step Type	Step Number	Period (s)	Circular Freq (Hz)
Mode	1	0.260	3.844
Mode	2	0.079	12.675
Mode	3	0.049	20.555

Fixing laser displacement sensors to the reference frame is the critical step of the measurements. As given in Fig. 5 each LDS was aligned to the same level with the corresponding floor. To accurately monitor the displacement of the each floor, all laser beams have carefully aligned as parallel as possible to the movement direction and could be always reflected from the lateral side of the floor without being of target. In order to compensate the LDS alignment errors that have been still present, a manual calibration procedure is conducted. First, shaking-table moved to the reference (center) point which corresponds to zero displacement. Then, it has moved with the steps of 10 mm in the range of +/- 90 mm, and for each displacement, mean value of LDS measurements was recorded. At the end, with the linear curve fitting method a compensation equation for each LDS is derived that directly gives the floor displacements (Fig. 7).

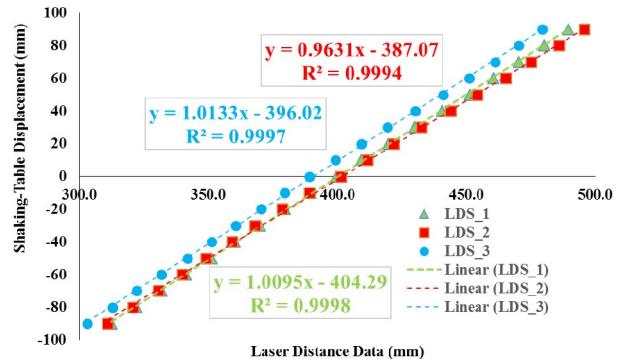


Fig. 7. Calibration data and curve fitting of each LDS

Table 4. Applied shaking-table movements

Movement	Amplitude	Frequency
30 cycle sine	20 mm	0.5 Hz
30 cycle sine	20 mm	1.0 Hz

30 cycle sine	50 mm	0.5 Hz
30 cycle sine	50 mm	1.0 Hz
Earthquake	El Centro (Normal)	
Earthquake	El Centro (Fast)	
30 cycle sine	20 mm	2.0 Hz
30 cycle sine	20 mm	2.1 Hz

After calibration procedure a set of movements were applied to shaking-table (Table-4). From start and at the end of test, total number of samples send from LDS-1, LDS-2 and LDS-3 are 64211, 64127 and 64422, respectively. As we say previously, measurement time is not constant and shows variation from one sample to another. We see that measurement time has almost 14 ms (%76.7, %71.4, and % 75.4) for all sensors. However, deviation of measurement time has a peak value of 59 ms for LDS-1, 52 ms for LDS-2 and 61 ms for LDS-3.

Table 5. Floor displacement amplitudes measured by LDS.

Motion Amplitude	Motion Frequency	Floor Displacement Amplitude (mm)		
		LDS-1	LDS-2	LDS-3
20 mm	0.5 Hz	21.04	20.73	21.13
20 mm	1.0 Hz	21.15	21.31	22.26
50 mm	0.5 Hz	51.01	50.96	51.04
50 mm	1.0 Hz	51.47	53.48	54.93
El Centro (Normal)		86.18	86.48	89.07
El Centro (Fast)		39.22	45.56	49.93
20 mm	2.0 Hz	20.82	23.27	24.43
20 mm	2.1 Hz	21.09	24.84	25.79

Measurement results of LDS displacements for each floor given in Table-5. As can be seen here, inter-story drifts clearly visible. In Fig. 8, FFT spectrum of LDS data for El Centro (Fast) earthquake motion. Here, mode shape and resonance frequency of the building can be practically determined which is estimated by simulations as 3.844 Hz.

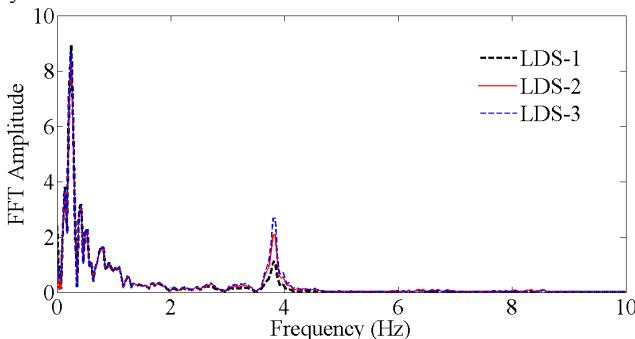


Fig. 8. FFT Spectrum of LDS data for El-Centro (Fast) earthquake motion

4. Conclusions

Non-contact displacement measurement system with multi-sensor support and an open-source software is successfully developed especially for small-scaled civil structural health monitoring applications. Fixing the laser displacement sensors to the reference frame is the most critical procedure that needs to be done carefully and dominates the measurement accuracy. In order minimize LDS alignment errors, a manual calibration procedure should be conducted before each measurement. With

a resolution of 0.1 mm and a measurement rate of 70 Hz, this real-time data logging system can be used especially for light structures and precise damping evaluations. It can be easily customized to integrate with another structural measurement system like strain-gauge, accelerometer, tilt-meter or linear potentiometers.

5. References

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