Processing of Signals Produced by Strain Gauges in Testing Measurements of the Bridges

Boštjan Kovačič\textsuperscript{a}, Rok Kamnik\textsuperscript{a}, Andrej Štrukelj\textsuperscript{a}, Nikolai Vatin\textsuperscript{b,}\textsuperscript{*}

\textsuperscript{a}University at Maribor, Faculty of civil engineering, Slomškov trg 15, 2000 Maribor, Slovenia
\textsuperscript{b}St. Petersburg State Polytechnical University, Politekhnicheskaya, 29, Saint-Petersburg, 195251, Russia

Abstract

Practical example of signal processing from strain gauge, inductive transducer and total station measurements are used to illustrate the features of the bridge load testing measurements. FFT provides accurate representation of physical behavior for static and dynamic signals obtained when loading the bridge. As a reference measurement the signal from inductive transducer was taken. A static part of the load test was also geodetically measured and theoretically calculated. The results are comparable.

Keywords: bridges, measurements, strain gauge, load test, deformation, strain, signal processing.

1. Introduction

The result of measurement of strain may be used for statements concerning the material stresses in the specimen, the nature and amount of forces acting on the specimen, etc. However, a strain to be measured is transferred faultlessly and free of loss. For that purpose, an intimate connection is required between the strain gauge and the object to be measured.
The description of a measured signal in three-dimensional representation including time, frequency, and amplitude is termed time–frequency representation. The time–frequency representation is suited for static load signals and dynamic load signals, for the measurement of vertical displacements and strains on structural elements. These measurements are carried out during the construction in order to control the system, after the construction for the purpose of monitoring the object and for reliability assessment after a certain time of use [1, 2].

2. Installation of strain gauges

The required intimate, plane connection between the specimen and strain gauge is best performed by special adhesive. The strain gauge can also be applied on the reinforcement bars of the bridge construction. (Fig. 1).

Fig. 1. Three strain gauges applied at one point on the bridge (measuring the strain in three directions)

There are many different methods for conducting a bridge load test. From a practical point of view, classical surveying methods such as trigonometric heightening and leveling are still used as well as the latest instruments. If possible, physical methods like measurements with an accelerometer [3], inductive transducer [4] and strain gauge [5, 6] should also be employed. In order to obtain results we analyze measured signals of the strain gauges, inductive transducers and accelerometers. Therefore laboratory tests and the corresponding analysis between measured results and analytically predicted values of vertical displacements are performed.

Bonding agents connect the strain gauge firmly to the surface of the specimen in order to transfer the deformation of the specimen correctly to the gauge. Various conditions and influences as well as consideration of the applicability require different bonding agents and installation methods. Bonding plays a most prominent role. The connection of bonded parts relies on the adhesion between the cement and the surface of the specimen. Adhesion is primarily based on adhesion forces between neighboring molecules. Various kinds of adhesives are offered depending on the working conditions at the place of installation and the various requirements of the effectiveness of the adhesive, especially, service temperature. Depending on the installation technology, one can differentiate between cold and hot curing adhesives and spot welding.

When possible we should use different type of measurements and to apply strain gauges on reinforcement before casting the concrete to obtain very accurate signal from the sensor, to protect the sensor from outer influences (weather, sun, snow, vandalism etc). If not possible the strain gauges can be glued on the surface of the construction.

3. Preparation of bonding surfaces and strain gauges

Strain gauges may be fixed to nearly all solid materials. The prerequisite for this is a suitable and careful preparation of the installation spot. In general materials can be divided on metallic and non-metallic (concrete, glass, plastic, wood, rubber) materials. The aim on metals surfaces is to provide a surface free of pores, cracks and oxide layers, which is not too rough but easily wetted. The individual steps should be in following in order: coarse cleaning (rust, scale, paints, thick layers of lubricants or dirt...), smoothing (rust, scar and deep scratches, humps...),
cleaning (dirt, grinding dust, grease,...), roughening, cleaning, marking, final cleaning and degreasing and alternatively pickling, rinsing and drying.

For coarse cleaning, scouring agents are recommended for removing grease or lubricated layers. Afterwards with clear or distilled water should be rinsed. Smoothing should be done with grinding, filing or other suitable methods. Grinding tools with exchangeable emery paper and rubber plates are best suited for this. Then the cleaning should be done again. Cleaning need to be done extremely carefully. It is possible to increase the bonding forces by enlarging the contact surfaces. Enlargement of the surfaces however is only possible by roughening. This is mostly done mechanically and only seldom chemically by pickling. Then the marking of the exact position of strain gauge should be done. A dry (empty) ballpoint pen should be used. If ink is still in the ballpoint pen, this must be removed with a solvent after the line has been drawn. The efficiency of the bonding forces decreases with the third to sixth power of the distance. Therefore, these forces should be limited to molecular layers. For that reason, very careful final cleaning is required (e.g. RMS1). [1]

The preparation of the bonding surface on concrete (Fig. 2) using rapid adhesive X60 (Fig. 3) is, in general, simpler than on metals, irrespective of whether the concrete was cast with oiled or dry mould forms. In the first case, the oil-soaked layer is removed with a grinder. Degreasing with solvents in not recommended. For dry covering, only the cement slurry is removed up to the solid concrete. Also in the case of dry mould form, grinding is recommended. Grinding dust is blown away using air pump or with oil- and water-free compressed air. Pores are completely filled with X60 adhesive.

On glass, glazed porcelain, enamel with X60, Z70 and EP250 it is possible to bond immediately to the degreased surface (Fig. 4). Roughening and other preparations are not necessary. Plastic are roughly divided into two groups which require different pre-treatment: soluble and non-soluble plastics. The physical or chemical treatments used on plastics serve to activate the molecular structure of the surface. The treatment of soluble plastics aims to remove all production additives, especially separation means like silicones or talc, lubricants like stearates, dirt from the surface and moulding skins on injection moulded parts. Care should be taken when using solvents for the treatment of plastics, since their action could cause swelling or stress corrosion. Wood may be cemented with the quick curing cement X60 after dry grinding with glass or flint paper. After degreasing with the solvents, rubber may be cemented with the fast curing cements X60 or Z70 (Fig. 5). Light roughening with emery might be necessary in some cases. [1]
Strain gauges are usually ready for use and do not require special treatment. However, if the bonding side of the gauge was touched with fingers or polluted in some other way, cleaning with a solvent on a Q-tip is recommended. The best and most commonly used method of the electrical connection between the strain gauge and the measurement lead (cable) is soldering. Similarly excellent connections are obtained by crimping. Clamp connections and plug connectors are not recommended. After all these preparations, visual inspection is needed. The strain gauge and the cable connections should be checked using a good magnifying glass with 6x enlargement, for following defects: air bubbles underneath the strain gauge, poor bonding at the edges, unreliable solder connections and flux residue. Installed strain gauges must also be protected against mechanical and chemical influences at the end of the installation process.

Summary

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4. Formulation of the signal processing

In order to measure all characteristic points on the bridge we should plan the load test in very early stages of building of the construction. For bridge load testing normally inductive transducers, accelerometers and strain gauges are used for the static and dynamic load test. Signal processing for all three sensor types are almost exactly the same so let’s focus only on one example of data processing for inductive transducer as a reference measurement.

At dynamic load test we mainly focus on that part of the measured signal when the construction freely oscillates.

The fundamental mathematical developments of the time–frequency representation have been originally introduced by Wigner [7]. Claasen and Mecklenbrauker [8] and Cohen [9, 10] give the theoretical and numerical developments of short-time Fourier transform (STFT), the Wigner distribution (WD), the Choi–Williams distribution (CWD) and the Zhao–Atlas–Marks distribution (ZAMD). However, in this article the Fast Fourier Transformation is introduced because it is still up to date and suitable for such tasks as written in [11] and [12].

We can transform raw measurement signal from a sensor from time domain into a frequency spectrum using FFT:

\[
\frac{1}{\sqrt{n}} \sum_{r=1}^{n} u_r e^{2\pi i (t-1)/(s-1)/n} \tag{1}
\]

where:
- \(u_r\) – data function,
- \(s\) – index of function,
- \(n\) – the length of the data.

On Fig. 6 a raw signal of inductive transducer in time domain is shown. Then we transform the signal using Eq. 1 into the frequency spectrum (Fig. 7) to do the signal correction caused by noises and to discard the tiny imaginary parts that appear due to numerical error. We also filtered the signal on the lowest and highest frequencies (low and high pass filter). The lower frequency boundary can be different and dependant on the specific equipment used (normally around 1 Hz – obtained from the manufacturer specifications). The upper frequency boundary can also be different but normally around 100 Hz because higher frequencies are not important for the construction. Corrected
signal is shown on Fig. 8. After the corrections we transform the corrected signal back to time domain using inverse FFT:

\[
\frac{1}{\sqrt{n}} \sum_{s=1}^{n} v_i e^{-2\pi i (r-1)(s-1)/n}
\]

(2)

On Fig. 9 the comparison of raw signal and the corrected one is shown. We can see that the corrected signal has less extreme values (peaks) than the original one.

Fig. 4. The raw signal of inductive transducer in time domain and The signal in frequency spectrum after FFT

Fig. 5. The signal in frequency spectrum after correction. The comparison of the raw (yellow) and corrected signal (red)
5. Experimental results

To demonstrate the use of strain gauges and signal processing and to determine vertical displacements and strains in laboratory the simply supported fabricated reinforced concrete beam (2700 x 75 x 80 mm) was prepared for load testing (Fig 10).

![Fig. 6. Scheme of concrete beam with measured points](image)

In order to achieve the best possible results, various tests using three inductive transducers LVDT, four HBM strain gauges and the Nikon total station were applied. On the concrete beam four strain gauges were applied. Strain gauges number one and three (SG-1, SG3) on the upper side and strain gauges number two and four (SG-2, SG-4) on the lower side of the beam. The beam was loaded in six stages. In first two stages 10 kg weights were added to the centre of the beam. Then 5, 2.5, 2.5 and 1 kg weights were added. Each added weight was geodetically measured with the Nikon total station and recorded with HBM’s analog-digital amplifier and Catman’s computer software. The switches were prepared in such manner that full, half and quarter Wheatstone bridge were simulated. On Fig. 11 the loading and unloading stages can be seen as increase or decrease of specific deformation at half Wheatstone bridge through time.

In Table 1 measured data for middle point (L/2) can be seen. Vertical displacement obtained by inductive transducer and directly measure with total station are very similar.

| kg | Strain gauge \( [\mu \text{m/mm}] \) | Inductive transducer \([\text{mm}]\) | Total station \([\text{mm}]\) |
|----|---------------------------------|---------------------------------|-----------------|
|    | SG –1,3                         | IND-1                           | G1   |
| 10 | -88.3666                        | -87.0042                        | -0.27 |
| 20 | -220.7666                       | -218.7250                       | -0.59 |
| 25 | -302.7875                       | -300.9583                       | -0.76 |
| 27.5 | -336.6125                     | -334.8583                       | -0.83 |
| 30 | -369.7000                       | -368.2167                       | -0.90 |
| 31 | -391.6667                       | -390.8333                       | -1.00 |

6. Conclusions

Practical example of signal processing from strain gauge, inductive transducer and total station measurements are used to illustrate the features of the bridge load testing measurements. FFT provides accurate representation of physical behavior for static and dynamic signals obtained when loading the bridge. As a reference measurement the signal from inductive transducer was taken. A static part of the load test was also geodetically measured and theoretically calculated. The results are comparable.
References

[1] K. Hoffmann, Practical hints for the installation of strain gauges, Hottinger Baldwin Messtechnik GmbH, Darmstadt, 1996.
[2] Ataei, Sh. 2005. Sensor fusion of a railway bridge load test using neural networks. Expert Systems with Applications, 2005 (29) pp. 678-683.
[3] Chowdhury, M. R., Ray, C. J. 2003. Accelerometers for bridge load testing. NDT&E, No. 36: 237-244.
[4] Sani, A. K. et al. 2000. Testing bridges by using tiltmeter measurements. Transportation Research Record, Vol 2, No 1697 pp. 111-117.
[5] Vurpillot, S., Inaudi, D., Scano, A. 1996. Mathematical model for the determination of vertical displacement from internal horizontal measurements of a bridge, SPIE Smart Structures and Materials, San Diego, USA.
[6] Stone, D. and A. Nanni, J. M. 2001. Field and Laboratory Performance of FRP Bridge Panels. Proc., CCC 2001, Composites in Construction, Porto, Portugal, Oct 10-12.
[7] Wigner, E. P. 1932. On the quantum correlation for thermodynamic equilibrium. Physics Review, Vol 40: 749-759.
[8] Claassen, T. A. C. M. and Mecklenbrauker, W. F. G. 1980. The Wigner distribution — a tool for time–frequency signal analysis. Philips Journal of Research, Vol. 35, 217–250.
[9] Cohen, L. 1995. Time–Frequency Analysis. Prentice-Hall Signal Processing Series, Englewood Cliff, NY.
[10] Cohen, L. 1966. Generalized phase-space distribution functions. Journal of Mathematical Physics, Vol. 7(5): 781–786.
[11] Meng, X., Dodson A.H., Roberts G.W. 2007. Detecting bridge dynamics with GPS and triaxial accelerometers. Engineering Structures, Vol 29: 3178–3184.
[12] Lin, C.W., Yang, Y.B. 2005. Use of a passing vehicle to scan the fundamental bridge frequencies: An experimental verification. Engineering Structures, Vol 27: 1865–1878.