Application of ambient vibration testing (operational modal analysis) in practice

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ABSTRACT: In this paper, practical problems to be dealt with when planning an ambient vibration based system identification test on a civil engineering structure are discussed. Practical problems include definition of the system boundaries, measurement point layout (grid density, measurement direction(s)), layout of the reference degrees of freedom, choice of sensor type and frontend parameter settings and length of the time window acquired per setup. Some problems are general, some are specific for railway bridges. The latter include the usual inaccessibility of the bridge deck top side and the necessary isolation versus ground of the sensors. The main part of this paper concerns the tests performed in the RFCS DETAILS project on the Erfttal Bridge on the Köln-Aachen railway line. In addition, some specific problems encountered with the tests on the Sesia Viaduct located between Milano and Torino are discussed.

1 BASICS

To experimentally identify the dynamic characteristics of a (civil engineering) structure, also referred to as system identification, two different methods are available:

- Forced Vibration Testing (FVT) and
- Ambient Vibration Testing (AVT).

With FVT, the structure is excited artificially and the transfer matrix $H$ is determined from the measured time signals of the introduced force $x_i(t)$ and the structural response $y_k(t)$ (Fig. 1).

With AVT, the structure is excited through (basically unknown) ambient forces and the (un-scaled) transfer matrix $H$ is determined from structural response signals only (Fig. 2).

To be able to concentrate on the basics this description is short but incomplete here.

![Figure 1: FVT test setup and processing scheme.](image1)

![Figure 2: AVT test setup and processing scheme.](image2)
We cannot discuss the problems of "FVT vs. AVT" for civil engineering structures and the latest developments in crossover methodologies here. This is done in e.g. Cantieni (2005), Masjedian et al. (2009) and Reynders et al. (2009). For the problem under discussion, an AVT test was the most reasonable solution.

2 GENERAL AVT TEST PARAMETER

To achieve reliable, good quality results, a number of parameters have to be optimized when planning an AVT experimental system identification investigation. First of all the question of the "unknown excitation" has to be discussed. The expression OMA, Operational Modal Analysis, which is also used in the context of what we call AVT here, can be misleading. OMA tries to tell us that we are investigating a structure being "in operation". To cite just three examples from the author's experience where OMA is simply a wrong expression: Bell towers, power stations (Cantieni (2009)) and railway bridges. In these cases the natural dynamic characteristics of the structure cannot be identified with the structure being "in operation". Simply because this operation is not of the "white noise" type and it is so strong that the structure's natural behavior is drowned in vibrations forced by "the operation". As a further example, highway bridges don't suffer from this problem. It is ok to test them while being "in operation".

Figure 3 illustrates the difference between the frequency spectra for the Erfttal railway bridge discussed here measured in an ambient and in an operational state: Among other effects, the train passage forces some vibrations with frequencies well below the bridge natural frequency $f_1 = 3.66$ Hz (see below). It was therefore one of the most severe problems in the case discussed here to find "train-free" time windows of sufficient length. Sufficient means: 1'000 to 2'000 times the period of the structure's fundamental natural vibration (Cantieni (2005)).

Figure 3: Frequency spectra for Erfttal Bridge measurement point 15 without and with a train passage. The bottom figure shows the two spectra overlaid. The cursor is set at 3.66 Hz in all figures.
Figure 4: Train time table for the Köln-Aachen (and reverse) tracks for the time slot 1…2.30 pm (ordinate). The Erfttal Bridge location is indicated with the vertical red line. Every crossing of a blue or black line with this line means a train passing the bridge. The two horizontal red lines indicate a 15 minutes time window with no train passages on the bridge. The thin solid black line indicates an ICE train.

To illustrate the expression "most severe", the time table for the trains passing the Erfttal Bridge in a 1.5 hour time slot is presented in Figure 4. There were a total of two 15 minutes train-free windows available each of the two testing days (see below). Problems of this kind did not occur for the M5 and Sesia viaducts also having been investigated in the DETAILS project.

Before taking off with an AVT test it should be clear that an ambient excitation (similar to white noise) with sufficient intensity exists. For the Erfttal Bridge the highway traffic passing underneath the bridge provides such a source of excitation in an optimum manner.

In the next paragraphs, more specific problems with test parameters are discussed in the context of the AVT tests performed within DETAILS on the Erfttal Bridge.

3 THE ERFTTAL RAILWAY BRIDGE

The Erfttal Bridge consists of two straight, parallel, composite filler beam girders, the northern and the southern bridge, separated by a 20 mm open gap. There is a 4 m difference in the longitudinal position of the two girders (Fig. 5). Each girder is a simply supported beam with a span length of roughly 25 m (Fig. 6). The two 1.1 m deep and 5.3 m wide girders are steel/concrete composite slabs consisting of eleven 1 m deep rolled steel beams HEM 1000 encased in concrete. The distance between two neighbouring steel beams is about 0.5 m (Fig. 7). Due to an unknown reason, the concrete quality is not the same for the two girders (B25 and B35 respectively). Each girder carries one ballasted railway track, with the ballast being continuous in the longitudinal as well as in the transverse directions thus covering the respective gaps between the girders themselves and between girders and adjacent tracks. The bridge is used by normal- and high-speed passenger trains as well as by freight trains.

Figure 5 gives further details on the bridge's situation. Adjacent to the southern Erfttal bridge, the S-Bahn bridge can be seen. This S-Bahn bridge is an old steel construction used by local railway traffic and is not subject of this paper. The parameters of the road underneath the railway bridge can also be seen in Figures 5 and 6: Two 4.3 m wide traffic lanes to the left, an adjacent grass strip and a sidewalk/bikeway to the right. The latter are very important when it comes to the question of how to realize the tests. In other words: It would not have been possible to perform the Erfttal AVT tests without these strips (details see below).
Figure 5: Erfttal Bridge, plan view. Dimensions: meters. The northern and southern bridges are subject of this paper.

Figure 6: Erfttal Bridge, longitudinal section. Dimensions: meters.

Figure 7: Erfttal Bridge, cross section. Dimensions: meters. The measurement point lines 1 to 4 correspond to the ones given in Figure 5.
4 INSTRUMENTATION LAYOUT PROBLEMS

Upon designing the measurement point grid layout, the following problems should be considered:

- how do the mode shapes to be expected look like?
- are we sure the points we assume to be fixed are really fixed?
- how dense should the measurement point grid be to determining the shapes with the necessary spatial resolution?
- should we measure in 1, 2 or 3 directions?
- how many references do we need to be sure to having at least one reference not sitting in a node for all modes and all setups?
- where should we place the references to cope with this same problem?
- how do we distribute the rovers to make sure having information on all substructures in all setups?
- what are our possibilities concerning the number of sensors and measurement channels being available for one setup?

In the context of the Erfttal Bridge, the answers were:

- the mode shapes calculated from the baseline FE model revealed that the bridge exhibits several major uncertainties: a), the action of the continuous ballast and rails on the system global and local stiffness, and b), the influence of the bridge bearings being elastomeric which also means: elastic, non-fixed in all directions.
- it is ok to measure in the vertical direction only; there is probably some bridge movement in the horizontal directions, especially longitudinally but it is ok to neglect this in a first attempt.
- the measurement point density was chosen to eleven points per span in the longitudinal bridge direction and to four measurement lines in the transverse direction (Figs. 5 to 7). The first meant to also including measurement points at the supports, the latter was chosen to cope with the relative movement between the two main girders.
- the number of references was chosen to four: two for each main girder at 0.3 and 0.4 of the span length L. This should allow easy determination of all modes of both girders with up to four transverse nodal lines along the span length (to be expected at 0.0, 0.5, 0.33, 0.25 L).
- as far as possible (see below) the rovers were located such that the measurement points were evenly distributed over the whole construction in every setup.

Collecting all sensors available at rci dynamics, KU Leuven and BU Weimar, a maximum of 16 identical sensors were available per setup. The rci dynamics LMS Pimento frontend offered 16 channels at the time (Fig. 8). This set the number of necessary setups to four. With the four references and 40 roving points, one setup consisted of 4 references and 10 rovers. This gave a strategic reserve of two sensors and two frontend channels. The measurement point grid is indicated in Figures 5 and 6. The measurement strategy is described in the next paragraph.
5 TESTING PROCEDURES

5.1 Spatial problems and problems in time

The spatial problems resulted from the fact that, a), the bridge was not accessible from the top side (owners of bridges for electrically powered trains tend to attempt killing every non-commissioned person trying to come close to their structures) and that, b), the highway under the bridge is a heavily trafficked motorway access road. The spatial restrictions set by the City of Kerpen were: At least one traffic lane has to be kept open all the time and a traffic light system has to be installed to control the single lane traffic flow. The temporal restrictions set were: A lane reduction is allowed for two consecutive days between 9 am and 3 pm.

These boundary conditions are not mentioned in the preceding section. They have however to be kept in mind when designing a test layout with some practical value.

Concerning the spatial problems the good news was the existence of the pedestrian/cyclist lane and the grass strip between the traffic and the pedestrian lanes. This allowed to place the measurement center vehicle during the two days of testing on the grass/pedestrian strip and to prepare/dismantle the scaffolding necessary to place and move the sensors before/after the single-lane-time windows in this region (Fig. 11). The cyclist lane was however not completely free of traffic. We had several near-misses between cyclists and test crew members during the two days of testing. However, no injuries, fortunately.

Another spatial problem to be coped with was the distance between bridge undersight and terrain being 5.4 m and the headway to being kept at 4.5 m. The first meant that fixing the sensors was not possible without using a scaffolding and the latter was definitely no fun-recommendation because there were many tractor-trailers passing underneath the bridge which used at minimum this regular headway. The grass strip was the only space where the cables could be lead from the bridge undersight to the terrain and then to the measurement center.

Figures 9 and 10 show the “war-plan” for the two days of testing, the sensor location schedule and the cabling philosophy. To keep life easy at least for the first day, everything was concentrated on the safe side of the open traffic lane (Fig. 9). The references had to be located such as to be reachable on both days (also keeping in mind their strategically necessary location!).

Figure 9: Test procedure layout for day 1, setups 1 and 2.
The dashed area indicates the lane kept open for traffic, MW = Measurement Center Van, arrows = dislocation of a sensor from setup 1 to setup 2.
Figure 10: Test procedure layout for day 2, setups 3 and 4. The dashed area indicates the lane kept open for traffic, MW = Measurement Center Van, arrows = dislocation of a sensor from setup 3 to setup 4.

Figure 11: This is how the test site looked like the first day of testing: Open traffic lane to the left, relative peace (crazy cyclists!) to the right.
5.2 Sensor application and cabling problems

The sensors used were piezo-electric accelerometers PCB 393B31 with a sensitivity of 10 V/g, a measurement range of ±0.5 g and a sensitivity of 10-6 m/s². The sensors were fixed to the steel beam bottom flange with magnetic supports (Fig. 13). An intermediate plastic layer provided electric isolation of the sensors from ground. This isolation should be ascertained in any case, but with bridges used by electrically driven trains, this is really essential.

To minimize the headway used by the instrumentation, the cables were fixed to the steel girders with small magnetic devices every two to three meters (Fig. 13).

Figure 12: This is how the test site looked the second day of testing (reverse angle of view as for Figure 11): Open traffic lane in the middle of the operation theater!

Figure 13: To the left: Accelerometer with isolating layer and magnetic fixation. Also visible on the picture to the right: Intermediate cable fixation using small magnets.
5.3 Data acquisition problems

Another challenge was choosing the measurement chain sensitivity and the time windows to store. On the one hand, an ambient test was to be performed. For this purpose, time windows of $T = 300...600$ s should be available where no train was crossing the bridge. Then, the measurement chain sensitivity should be as high as possible. The train schedule on this bridge is so dense that for each net setup time of roughly 1.5 hours one time window with ambient conditions for more than 10 minutes could be identified from the time table only.

On the other hand, some crossings of high-speed trains should also be acquired. Here, the measurement chain sensitivity should be such that no overloads would occur while converting the data from analog to digital.

The signals measured were conditioned with an LMS Pimento 16-channel front-end (Fig. 8). The sampling rate was chosen to $s = 500$ Hz, digitization was performed with a 24 bit resolution. For AVT purposes, a sampling rate $s = 100$ Hz would have been sufficient.

Pimento offers four different input sensitivities: 0.316, 1, 3.16 and 10 Volts fullscale. Therefore, because the AVT tests were of primary importance, the input voltage was chosen to 0.316 Volt first. Files 001 and 002 the spectra of are shown in Figure 3 were acquired with this value. As the train passing in file 002 was no "bad guy", no overloads occurred. This input range was kept whenever one of the four expected "train-less" time slots was expected. With the result that all them were overloaded through a train not really keeping the schedule. These files had to be truncated before being used for AVT data processing (see below). To acquire the data for an expected ICE train crossing the input range was set to 10 Volts (File 022, Fig. 17).
Checking of the signals presented for Test 022 in Figure 17 yields:

- the ICE train generated an acceleration amplitude of 1.65 m/s² in point 15.
- the amplitude of ambient vibrations was about 0.00201 m/s² in point 15.
- the amplitude generated by the ICE train is about 820 times larger than the amplitude of the ambient vibrations.
- (by the way: the spectrum of the complete time signal shows similar effects as presented in Figure 3: Useless for system identification purposes.)

Therefore: Choosing the sensor type and the frontend parameters for a longterm monitoring system is a comprehensive task. The requirements concerning system dynamic range are extremely high for both hardware systems. It is otherwise not possible to cope with the requirements for tracking of the bridge natural behavior and of its behavior under train passages with the same equipment. Fortunately, modern frontends offer a 24 bit ADC resolution. It remains the task of choosing a sensor providing the necessary dynamic range.

6 DATA PROCESSING

During the two days of measurement, 23 files were acquired. As the trains did not really keep the theoretical schedule, all files with "ambient" conditions had to be truncated because an unexpected train, usually overloading the measurement chain, had appeared, mainly at the end of the time window acquired. For this purpose, a MatLab routine was written by a colleague from
GeoSIG which allowed cutting a "good" piece of signal out of a measured signal. The LMS Pimento software does not allow such a signal treatment. Finally, the dynamic characteristics of the bridge could be extracted from four files, one per setup, with ambient conditions for a mutual minimum $T = 410$ s length.

Figure 18 gives an overview of the measurement point layout for the four setups. The general strategy is: As far as possible, each setup includes information on all substructures.

![Figure 18: Measurement point layout for setups 1 to 4; blue: references, green: rovers.](image)

Applying the Artemis Software Suite and making use of the EFDD (Enhanced Frequency Domain Decomposition) routines allowed identification of 13 bridge modes in the frequency range $f = 3.68...41.1$ Hz (Figures 19 to 21). By decimating the data by a factor of 5, the Nyquist frequency was reduced to $f = 50$ Hz. The SVD diagram presented in Figure 19 shows that the number of projection channels was chosen to 4. The number of frequency lines for $f = 0...50$ Hz was chosen to 512.

Application of the Artemis SSI UPC routines yielded an additional mode 4a at $f = 13.71$ Hz. Whereas mode 4 at $f = 13.24$ Hz is the second bending mode with the two girders being in phase, mode 4 is the second bending mode with the girders being out of phase. It is not clear why it was not possible to separate these modes using the EFDD technique.

![Figure 19: EFDD SVD diagram.](image)
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<th>Damp. ϶ [%]</th>
<th>σς [%]</th>
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<td>41.11</td>
<td>0.15</td>
<td>0.20</td>
<td>0.08</td>
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Figure 20: Natural frequency f, standard deviation σf, Damping in percent of critical, ϶, and standard deviation, σς, for the 14 modes identified for the Erfttal Bridge.

Figure 21: Frequencies and shapes of the first seven Erfttal Bridge natural modes. Although the number of uncertainties was very large (continuous ballast and rails, elastic bearings etc.), based on these modes and the sophisticated updating software Package OptiSlang, the colleagues of BU Weimar were able to extract an optimally updated Slang Finite Element model (Brehm et al. (2009)).
7 SESIA VIADUCT AVT INVESTIGATION

7.1 General

Courtesy of Bart Peeters and Giuseppe Chellini, the information presented in this Chapter is taken from Chellini et al. (2008). This IMAC paper contains further details on the tests performed on the Sesia Viaduct in the context of the DETAILS project.

7.2 The bridge

The Sesia Viaduct is located on the Torino-Milano high-speed railway line and carries two ballasted railway tracks over the Sesia River close to the City of Novara. The viaduct is a 322 m long composite box girder structure designed in 2003 and consists of seven 46 m long simply supported girders (ballast continuous). The twin-box steel girder with an overall width of 13.6 m and a constant depth of roughly 3.4 m is covered by a 0.4 m thick concrete deck from prefabricated slabs (Fig. 22). The connection between the two is ascertained through studs.

![Figure 22: Cross section and overall view of the Sesia Viaduct.](image)

7.3 General AVT test parameter

The Torino-Milano high-speed railway line not yet being completed, no problems with "train-free" time windows occurred here. The number of trains crossing the bridge was less than ten per day. Experience shows that no problems with an ambient excitation of such structures occur. Wind and other ambient sources tend to nicely excite any slender structure of more than 300 m length and composed of 46 m spans. Testing of this bridge required one week.

7.4 Instrumentation layout problems

The measurement equipment available not being unlimited, the AVT test had to be concentrated on one of the seven bridge spans, span number 2 from the Torino side. Measured degrees of freedom (DOF's) included vertical as well as horizontal transverse directions. In addition, the horizontal longitudinal movement was registered at the supports. Following a respective discussion in one of the DETAILS' meetings, the two neighbouring spans number 1 and 3 were instrumented too (Fig. 23). The problem with bridges being composed of a good number of identical, simply supported spans is that "simply supported" sounds very easy but, as a matter of fact, it isn't. With such a structure, the various spans interact dynamically for any kind of support condition. Interaction of this kind can even be observed between completely separated twin bridges. As the single spans tend to exhibit similar natural frequencies it is usually close to impossible to reliably interprete the vibrations measured in one of the spans only.

The instrumentation layout chosen in the first three spans of the Sesia Viaduct Torino side is shown in Figure 23. A total of 103 measurement points were instrumented with 33 sensors, 6 of them being reference points, the remaining rovers. As can be seen from Figure 23, the measurement point grid is directed towards identifying local modes of the beam bottom steel plate in some cross sections.
Figure 23: Sesia Viaduct AVT measurement point layout in the three spans at the Torino side. References are shown in red. For each span, the 15 cross diaphragms are numbered from 1 to 15 from the Torino to the Milano side. The measurement center was located on the pier between spans No. 1 and 2.

7.5 Sensor problems

Of the 33 sensors, 10 were of the capacitive and 23 of the piezoelectric type. The signal conditioning electronics not being identical a significant phase lag between the time signals acquired with the two types resulted. This had to be corrected for when extracting the mode shapes.

7.6 Signal dynamic resolution problems

The problems with using the same measurement chain for acquiring bridge vibrations excited through "simultaneous" ambient excitation and train passages as for the Erfttal Bridge tests occurred with the Sesia tests. This is nicely documented in Chellini et al. (2008). Using 10 V/g sensors and the 10 V frontend input range yielded good results. However: The analog-to-digital conversion has to happen with a 24 bit resolution. Otherwise, the quality of the signals excited through ambient sources is not sufficient (Fig. 24).

Figure 24: To the left: A signal acquired under ambient excitation and also including a train passage. To the right: A part of the ambient signal converted with 16 bit (top) and with 24 bit (bottom).
7.7 Testing procedures

Sesia Viaduct AVT testing was basically free of procedural problems. The crew could move freely inside the box girder, place the sensors and frontend where they liked and take measurements when they liked. They had only to make sure the power generator did not run out of gas.

7.8 Results

The two fundamental bridge modes are shown in Figure 25. Further results can be taken from Chellini et al (2008).

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**Figure 25**: The shapes of modes 1 and 2 differ in the phase lags between the three spans only.

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8 SUMMARY

Practical problems to be dealt with when planning an ambient vibration based system identification test are discussed. These include definition of the system boundaries, measurement point layout, layout of the reference degrees of freedom, choice of sensor type and frontend parameter. Some problems are general, some are specific for railway bridges. The main part of this paper concerns the tests performed in the RFCS DETAILS project on the Erfttal Bridge on the Köln-Aachen railway line. In addition, some specific problems encountered with the tests on the Sesia Viaduct located between Milano and Torino are discussed.

9 REFERENCES


