Some conclusions from the measurements of temperatures and their gradients on eigenfrequencies of bridges

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ABSTRACT: The ambient air temperature and solar radiation are affecting the soil and asphalts' stiffness and hence the eigenfrequencies of a bridge. Very often eigenfrequencies are automatically determined by special algorithms from structural response data generated by ambient excitation and measured by permanently installed sensors that is sometimes called "output only analysis" or "operating modal analysis". Additionally the ambient air temperature is registered and finally the eigenfrequencies are analyzed versus the air temperature. The graph is normally a scatter diagram and each point is one measurement. In general the eigenfrequencies decrease with increasing temperature, whereas often linear regression is used to determine the line of best fit. But the slope of this straight line and the width of the scatter around the regression line differ from bridge to bridge. Especially this scatter field around the mean value at a determined temperature complicates the detection of damage, which is also often based on eigenfrequencies' reduction. Hence the difficulty among others consists in separating damage from environmental effects.

In Luxembourg the eigenfrequencies of a new two field composite bridge with steel girder, concrete slab and a relative thick asphalt layer were monitored over years. Additionally several temperatures at different points of the structure were registered. The eigenfrequencies were determined by Stochastic Subspace Identification (SSI). It turned out that the slope of the first eigenfrequency versus temperature is extremely high with 7‰ per °C and that any part of the bridge has at any moment its own temperature. Hence the bridge is not characterized by only temperature and moreover the temperature difference between steel and concrete is essential for the deviation from the mean value of the eigenfrequency at a given structural temperature. Especially in summer the day and night variations of ambient temperature are high due to the high solar radiation and hence the temperature gradients in the bridge are important, whereas in winter with overcast sky the gradients are small. It can be shown that the temperature gradient between steel base frame and top concrete slab is influencing the measured eigenfrequency. This knowledge is of high importance prior to the analysis of the data for damage detection and a simple reduction of the related uncertainty is possible by using only days with low temperature gradients for damage detection.

KEY WORDS: damage detection; bridge inspection; temperature influence on eigenfrequencies.

1 INTRODUCTION

For structural health monitoring the eigenfrequencies are seen very important characteristics of a structure and often monitored and used among other parameters as damage indicators. It is known that damage reduces the stiffness and hence the eigenfrequencies of a bridge; unfortunately there are other environmental parameters aside, also influencing the eigenfrequencies as for instance the ambient temperatures. These environmental conditions also change the structures' stiffness and hence the modal parameters, though they are independent of damage. Hence it is very important to separate temperature effects from damage effects.

For instance, Peeters et al. [1] show in Figure 1 the first eigenfrequency of a bridge in Switzerland versus the ambient temperature. In the range between 0°C and 40°C one may use linear regression to approximate the data and to establish a relation between the first eigenfrequency and the temperature $f_1 = a \cdot T + b$. In this example the slope "a" is approximately 1‰ per °C and the bandwidth of the scatter diagram is approximately 2,5%. Neither this bandwidth nor this slope "a" are general constants, but are different for individual bridges.

Some other examples of monitored bridges may be found for instance in Link et al.[2] and Moaveni et al. [3]. In Figure 1 another interesting effect may be seen at temperatures below

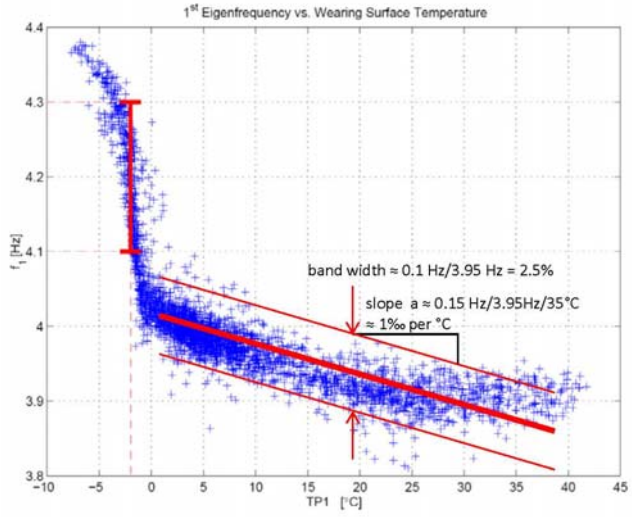

Figure 1: First eigenfrequency f_1 of the Z24-bridge versus ambient temperature [1]

0°C, where the stiffness of the structure and/or the bearing conditions change significantly probably due to freezing.
One may summarize that the characteristic eigenfrequencies versus temperature of an individual bridge has to be known prior to damage assessment to separate temperature effects from damage effects. The larger the bandwidth of this scatter diagram the more difficult becomes damage detection, as it adds uncertainty to any identified eigenfrequency. Severe damages of concrete bridges cause reductions of the eigenfrequencies in the order of magnitude of 10% as for example may be found in Waltering [4], Bungard [5], Maas et al. [6] and Mahowald [7].

It is hence of great importance to reduce the bandwidth and to know, what parameters are effecting it prior to temperature effect correction and prior to damage assessment. It will subsequently be shown by measurements that temperature gradients within the structure are also influencing the eigenfrequencies.

2 MONITORING SYSTEM

The investigated bridge is located in Useldange over the river Attert in Luxembourg. It is a composite two-span bridge with a total length of 37.3m divided into two fields of 23.9m and 13.4m span lengths as sketched in Figure 2. The upper plate has a thickness of 25cm and is made of concrete C45/55. This concrete plate is held by four main longitudinal steel girders of S355 with heights ranging from 0.5m to 1.3m following the bending moment. Two steel longitudinal girders are connected to each other with transversal girders every 4m. Above the concrete plate is an asphalt layer of 25cm, which is relatively heavy compared to common thicknesses of 8cm to 10cm (Bungard [5]). It should also be highlighted that this bridge has two fixed (or let us better say more or less clamped) supports: one at the south side and one at the column in the middle. A sliding support is located at the north abutment.

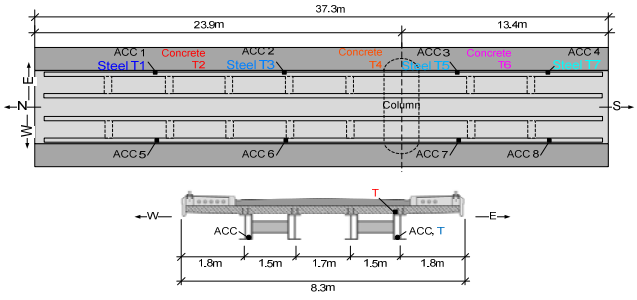

Figure 2: Positions of the temperature transducers and the accelerometers on the bridge for monitoring (Bungard [5]).

The time data is recorded using 8 accelerometers of type PCB 602A13 with sensitivity of approximately 1000mV/g and by 7 temperature sensors PT-100 JUMO WTH 90.2522 installed on the bridge as shown in Figure 2. The acceleration data was captured daily from 2:00 to 22:00h with a sample rate of 200Hz while the temperature sampling was done with 1Hz by the acquisition system HBM MGC-Plus and the software Catman professional. The data is written in ASCII-format and zipped in order to reduce file size. The installation of the transducers and the acquisition system took place in 2006 and the monitoring began in January 2007. The analysis of the data and the identification of the modal parameters are done with the Stochastic Subspace Identification (SSI) [8] method, which was programmed in Matlab. First the files were unzipped and then the 1Hz and 200Hz data were identified. In order to find a relation between the eigenfrequencies and temperatures a matrix containing the identified eigenfrequencies and temperature values of the seven transducers versus time was established. To shorten the size of the data the analysis time period is reduced from 1s to a time period of 15 minutes in the following way. The temperature values are simply averaged over 15 minutes, whereas the eigenfrequencies are more difficult to be grouped into these time intervals. Therefore an arbitrarily threshold value of $0.0015 m/s^2$ is defined and the acceleration data is scanned, using a rolling window of 4s (800 samples) in length and 1s (200 samples) moving rate to identify dynamic events, i.e. events when the bridge is under vibration. Figure 3 shows for instance acceleration data, where clear traffic periods can be recognized. For each dynamic event, Stochastic Subspace Identification (SSI) is performed to identify the eigenfrequencies from the data of 4 accelerometers. The average of the eigenfrequencies for each eigenmode is calculated over all events in the 15-minute time period and written in the final data matrix.

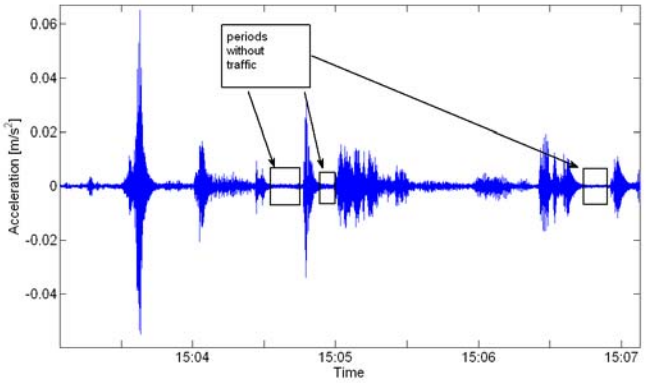

Figure 3: Example of time data of one accelerometer describing traffic periods and non-traffic periods.

3 MONITORING RESULTS

Figure 4 shows the 7 temperatures of the steel girders at the lower side of the bridge and inside the concrete plate, which is located more topside but still underneath the asphalt layer. The exact positions of the transducers are shown in Figure 2 with the same colors as in the figures below. There are 4 temperature transducers at the steel bars (T1, T3, T5 and T7) and 3 within the concrete plate (T2, T4 and T6). Additionally the first eigenfrequency is shown in green with a second vertical axis on the right side. It has to be explained that the empty spaces in April and November are due to an acquisition system failure. Furthermore it should be noted that the system paused also between 22:00 and 2:00h, which cannot be seen in Figure 4. We see clearly a yearly temperature variation and in an anticyclical pattern the first eigenfrequency. Hence a strong dependency of the latter on the temperature is evident.

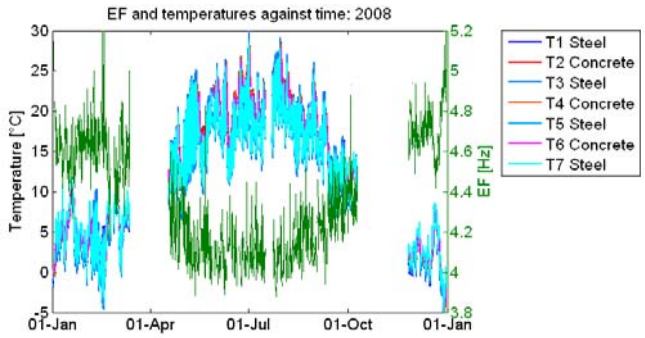

Figure 4: Different temperatures of steel and concrete (in blue and red) and the first eigenfrequency (in green) of the bridge in the year 2008.

We zoom now into smaller time intervals to see the daily influences of the temperature, why one should distinguish between winter and summer months. Figure 5 shows the daily temperatures of a sunny day in June 2008 and **Error! Reference source not found.** of a sunny day in February 2008. During the summer months variations between day and night of 10K for the steel are registered. Furthermore differences between steel and concrete of around 6K can be noticed. The variations of the steel-temperatures are higher than the concrete temperature variations due to the smaller thermal inertia, which additionally leads to a phase shift of approximately 7 hours between steel and concrete. This is due to the fact that the temperature transducers for the steel girders are attached to the outside on the surface of the steel work and not inside the material as the concrete sensors are. The eigenfrequencies are higher during the night than during the day due to the changed stiffness. Considering now some sunny winter days in Figure 6 the temperature variations at the steelwork between day and night are 8K and the differences between steel and concrete are only 3K. Here the time shift of approximately only 5 hours is observed and the eigenfrequencies also vary inversely to the structure temperature. Now we look in Figure 7 to a time period with overcast sky in December, when the temperature differences between the steel and the concrete are not so pronounced and thus clearly lead to smaller variations of the eigenfrequency. These weather periods are far better for measurement and damage detection than sunny days with high gradients.

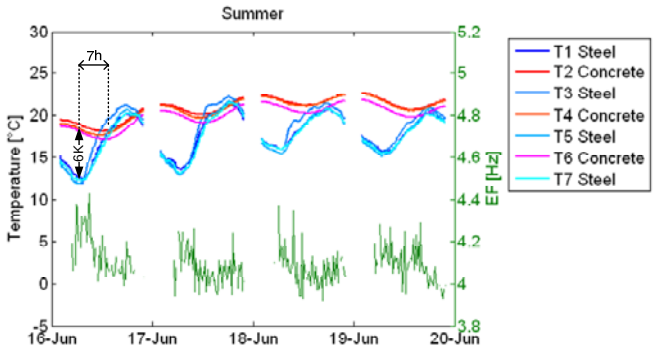

Figure 5: Some sunny summer days of June 2008

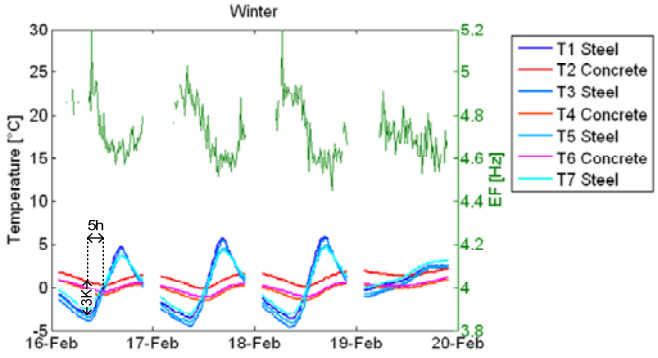

Figure 6: Some sunny winter days of February 2008

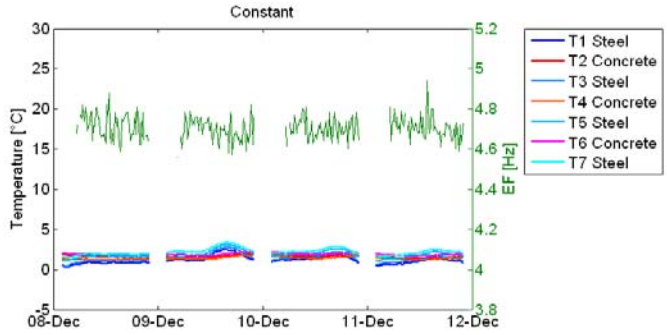

Figure 7: Some cloudy winter days of December 2008

The question arises how exactly the temperatures of steel and concrete are linked to the eigenfrequencies and whether there is at all a temperature which may be denoted as "the" structure temperature. Therefore the first eigenfrequency is plotted against the concrete temperature T2 in Figure 8. We can clearly see increasing eigenfrequencies (black "+") with lower temperatures as expected. The relation is quite linear as the regression line in red shows. Moreover the standard deviation σ=0.10 Hz was calculated with respect to the regression line and not with respect to a constant mean value. The eigenfrequency band of $\pm 3 \cdot \sigma$ width is shown; meaning for one specific temperature an uncertainty of 0.60Hz which is equal to 0.60Hz/4.5Hz ≈ 13% and hence an extremely high value.

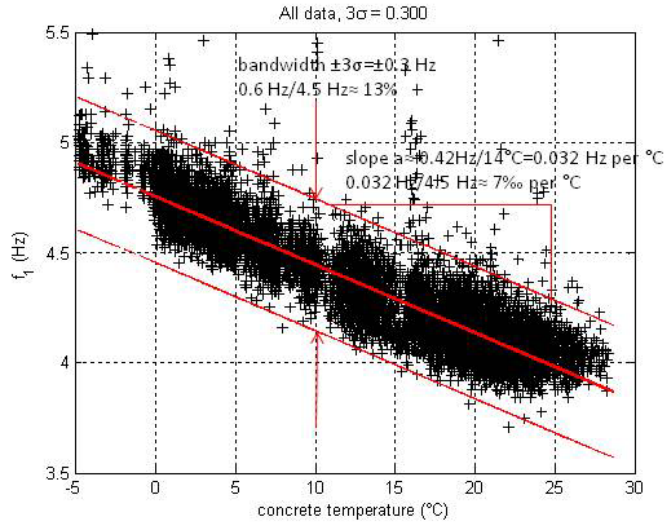

Figure 8: First eigenfrequency f_1 versus the concrete temperature T2 of the bridge in Useldange for the year 2008.

This band width of ±3 times the standard deviation (σ=0.10 Hz) is reflecting measurement uncertainties and non-linear effects of the structure and the bearings. A big truck for example creates a far higher excitation than a small motorcycle. For instance Waltering [4] and Mahowald [7] showed that concrete structures and big bridges behave non-linear in the sense that their eigenfrequencies are a bit dependent on the level of force excitation. Bungard [5] showed for this bridge in Useldange a variation range of the eigenfrequencies of less than 2.5% with swept sine excitation. High excitation forces lead to lower eigenfrequencies and vice-versa. But relative variations of 13% are really high and can not only be caused by this non-linear effect of force excitation dependency. Therefore the same eigenfrequencies were analyzed in Figure 9 for different temperature gradients $\Delta T=T1-T2=T_{Steel}-T_{Concrete}$. Again, linear regression lines were calculated for different temperature gradient intervals. One can recognize that for each regression line the slope "a" is approximately the same for all ΔT-intervals, whereas the offset value "b" (eigenfrequency at 0°C) is lower for high temperature gradient ΔT intervals. These "b"-values vary about 5% from low ΔT to high ΔT, which is due to changed boundary conditions and Young's modulus and not due to damage (see also Table 2). Additionally it should be noted that the slope-value "a" is extremely high and extremely uncomfortable with ≈ 0.032Hz/°C ≈ 0.032Hz/4.5Hz/°C ≈ 7‰ per °C. This means that 20°C of concrete temperature change will result in 14% change of the first eigenfrequency, which is even higher than typical changes due to severe damage [4], [5], [6], [7].

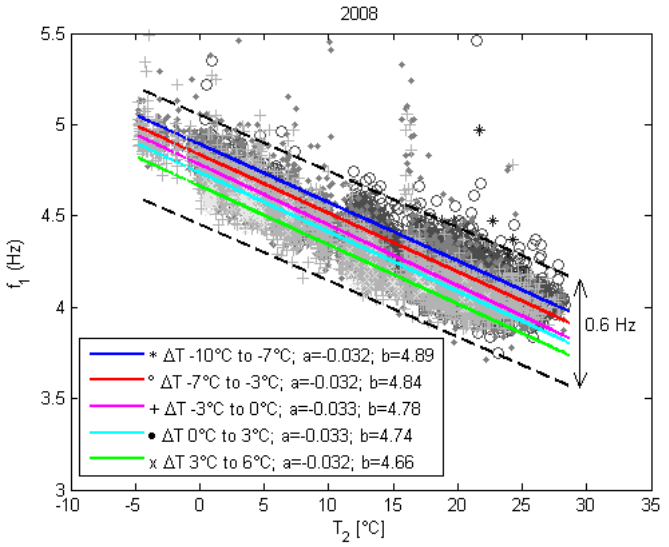

Figure 9: First eigenfrequency versus the concrete temperature T_2 of the bridge in Useldange for the year 2008. $\Delta T = T_1 - T_2$.

In Figure 10 the concrete temperature T2 is not indicated and all sampling points in each temperature interval ΔT are shown, which are of course not equally distributed as the intervals with small ΔT appear more frequent and thus are statistically more confident. Additionally the standard variations σ with respect to the linear regression lines in Figure 9 (and not with respect to constant values) were calculated for each interval. The ΔT-intervals with absolute large values occur of course less frequent and are hence less confident though the standard-variations σ are quite similar.

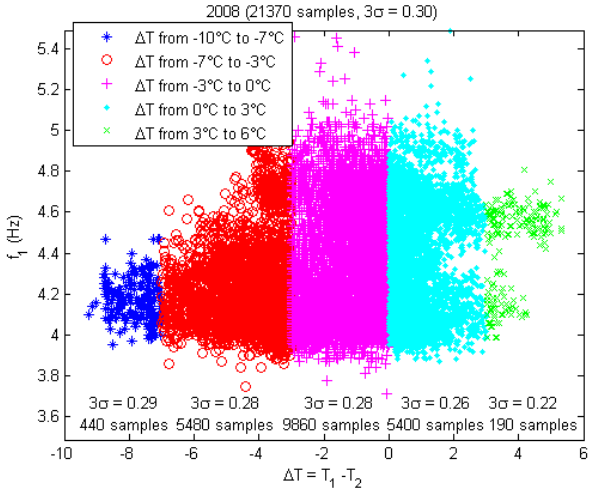

Figure 10: Identified first eigenfrequencies with SSI in 2008 versus temperature gradients ΔT with indication of number of identifications n and standard deviation σ with respect to the linear regression line per interval.

Hence the different gradients ΔT are very important and should be further studied in order to reduce the bandwidth ±3·σ, the bandwidth of uncertainty for a given concrete temperature. The temperatures between 0°C and 15°C were now selected because freezing effects and high radiation effects in summer were considered as extreme scenarios where measurements should be avoided. In Figure 11 the days of constant thermal conditions as indicated in Figure 7 were selected by imposing a limit for temperature changes, i.e. imposing $d(\Delta T)/dt < 0.1°C/h$ and $dT_2/dt < 0.1°C/h$ (blue data).

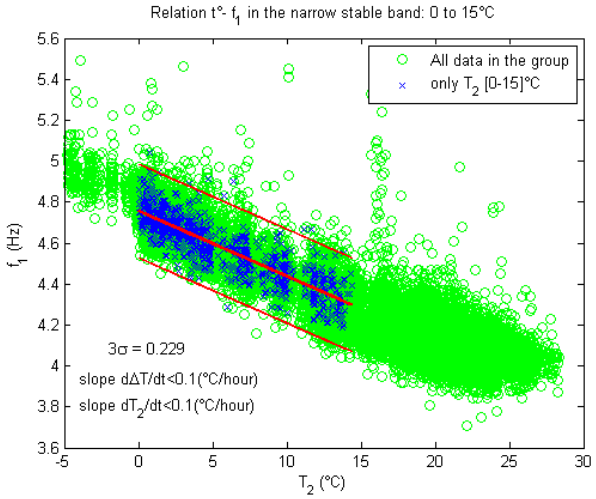

Figure 11: First eigenfrequency versus the concrete temperature T_2 of the bridge in Useldange for the year 2008. The green "o" are all data and the blue "x" are only data with T_2 between 0-15°C and slope $d(\Delta T)/dt < 0.1°C/h$ and $dT_2/dt < 0.1°C/h$

For the blue selected data in Figure 11 the standard deviation

σ=0.076 Hz was calculated with respect to the regression line and a band of ±3·σ=±0.229 width is shown. Hence the bandwidth could be reduced by 24% from 0.3 to 0.229 Hz.

In 2009 there were again problems with the monitoring system and the number of sampled eigenfrequencies was very small and hence these measurements are not presented here. The data of 2010 are not shown as they are quite similar to the data of the year 2008.

The following Table 1 and Table 2 summarize now the calculated slope values "a" and the offset values "b". For the year 2009 the values were not very accurate, since the data acquisition broke down. The inaccuracies occur if only very few values within a ΔT interval are available, especially for the intervals -10K to -7K and from 3K to 6K. These rather unsure values are marked by an asterisk (*).

ΔT *[°C]*	*-10 to -7*	*-7 to -3*	*-3 to 0*	*0 to 3*	*3 to 6*
2007	-0.025*	-0.033	-0.033	-0.033	-0.025*
2008	-0.032	-0.032	-0.033	-0.033	-0.032
2010	-0.028	-0.030	-0.031	-0.031	-0.029

Table 1: Slope "a" in [Hz/°C] for some years for the bridge in Useldange.

ΔT *[°C]*	*-10 to -7*	*-7 to -3*	*-3 to 0*	*0 to 3*	*3 to 6*
2007	4.76*	4.86	4.79	4.73	4.57*
2008	4.89	4.84	4.78	4.74	4.66
2010	4.93	4.89	4.82	4.77	4.70

Table 2: Eigenfrequency at 0°C or "b"-value in [Hz] for some years for the bridge in Useldange.

One can clearly see the parameters "a" does not vary a lot, considering small temperature gradients only. Over the years a constant value can be assumed. Also the "b" values stabilize in a specific interval, but clearly show an increase of approximately 0.05 Hz or 1% per ΔT-interval.

4 SUMMARY AND CONCLUSIONS

The Useldange-bridge in Luxembourg was monitored for four years. 7 different structural temperatures were registered and furthermore the eigenfrequencies were determined based on output only measurements with the Stochastic Subspace Identification (SSI) algorithm. The two span bridge has the specialities of two fixed or strongly clamped supports and an additional sliding support. Furthermore it has a very thick asphalt layer. Both characteristics lead to a high temperature dependency of the eigenfrequencies with slope value of 7‰ per °C. The characteristic behavior of eigenfrequency over the structural temperature must be known prior to damage assessment for any individual bridge in order to separate environmental effects from damage. The bridge of Useldange which was discussed here is perhaps an extreme case and therefore an interesting example.

It could additionally be shown that the temperature difference between outer steel work and the concrete slab influence the first eigenfrequency by approximately 5% in average (Table 2). This important effect has to be considered when temperature compensation is done. A very simple but effective way for reducing this effect is to use the data only, when the temperature differences are small. Small temperature gradients occur after sufficiently long cloudy weather periods with overcast sky. For these days the uncertainty or ±3·σ bandwidth can be reduced by ¼.

Further research has to be done in order to reduce this bandwidth by more detailed analysis of the temperature effects and other influencing parameters, as for instance the excitation amplitude dependency and measurement noise in general.

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