Michael Österreicher, Alfred Strauss[2], Roman Geier[3]

[1] iC consulenten Vienna, Austria
[2] University of Natural Resources and Life Sciences Vienna, Austria
[3] Schimetta Consult Vienna, Austria

1 INTRODUCTION

Today's society is marked by a constantly increasing need for mobility. The new strains caused by faster means of transport and bigger carrier loads require a large number of structures to be tested for stability and reliability. In addition, measurements and analyses are aimed at increasing the lifetime of structures by enabling specific and cost-effective interventions, thereby reducing the life cycle costs of the structure.

In recent years, vibration measurements (acceleration measurements) have increasingly been applied in the analysis of structures. Such measurements are easy to perform and cost-effective but they only provide "indirect" parameters (acceleration, natural frequency, damping). The so-called direct measurements (e.g. deformation, tension, strain gauge), however, require much more complex measuring technology, which in turn makes them more cost-intensive.

2 PROBLEM DEFINITION

The selection of measuring points for vibration measurements, in particular on large objects, is an important criterion for the significance of the measurement results/analyses as well as for the cost-effectiveness of the measurements. While such measurements are required to provide indications of possible structural damage that should be as accurate as possible, the number of measuring points should, at the same time, be kept to a minimum to make such analyses cost-effective.

Hence, the location and number of measuring points has to be optimised to guarantee significant results.

3 CURRENT PROCEDURES

Currently, every newly erected bridge in the Austrian Federal Railways' national network is subjected to a structural load test before the appropriate section is brought into service. In general, such load tests are carried out by positioning several locomotives or fully loaded goods wagons on the bridge and subsequently measuring the resulting deformation. This deformation is then compared with the one produced in from the computational model. If the measured deformation lies within a predefined range of values, the structure conforms to the requirements and regular service can be started. The problem with such load tests is that the resulting data have no relation to the actual stress a railway bridge is subjected to. In particular, the lack of dynamic loading on the structure in the course of such analyses is a major problem.

Existing railway bridges whose load capacity and remaining lifetime are to be determined are currently subjected to vibration and/or deformation measurements as well as to tension measurements. Vibration measurements are the preferred method from an economic point of view.

The selection of measuring points used in vibration measurements as well as the description of the analysis procedure are currently not included in any standard. First attempts in this direction were made by a research project aimed at establishing guidelines for vibration measurements. The following approach was taken to the selection of measuring points:

In single-span bridges, the maximum impact occurs in the midspan. In order to determine the natural frequencies up to the fourth harmonic, a second point is best chosen at approx. 0.3 to 0.4 x. An addition, a measuring point has to be placed off the axis of the structure to identify torsional vibration.

This simple measuring layout shows that such a generalisation can only be easily applied to "simple" structures (straight single-span bridges). Such a simplified selection of measuring points is not suitable for more complex or for leaning load-bearing structures (bridges). The selection of measuring points is of particular importance in successfully identifying defective parts of structures through vibration measurements. An appropriate selection of measuring points minimises their number and reduces the costs of the measuring programme.

4 APPROACH

In order to achieve the above objective, a procedure has to be identified with which the position of the sensors can be determined according to the damage pattern to be identified.

The below procedure for verifying the significance and optimising the position of measuring points is based on probabilistic methods combined with a finite element (FE) simulation.

In a first step, a system $\boldsymbol{S}$ is analysed whose response behaviour is determined by a number of basic variables. The procedure is aimed at determining how a change in basic variables at certain points in the system affects its response behaviour. For this purpose, system $\boldsymbol{S}$ is divided into $\boldsymbol{N}$ sections. In each of these sections, $\boldsymbol{n}$ random permutations of random numbers are created. The objective is to determine the impact that various sections have on the response behaviour of the structure through a minimum of numerical simulations. The random numbers are generated through Latin hypercube sampling (LHS). The LHS system as well as the importance sampling system are variance-reduction simulation procedures. Their advantage lies in the fact that, in contrast to other simulation techniques (e.g. Monte Carlo, where the majority of simulation values lie in the medium range), the entire distribution range of variables can be captured with relatively low number of samples ($\boldsymbol{n}$).

The impact that various sections have on the response behaviour is subsequently illustrated in the form of a rank correlation. The rank correlation coefficient is parameter-free and measures correlations, i.e. it measures how well an arbitrary but monotonous function can describe the correlation between two variables without making any assumptions about the probability distribution of the various random variables.

In contrast to Pearson's correlation coefficient, the rank correlation coefficient does not require the assumption that the relation between the variables is linear nor do the variables have to be measured on an interval scale. This article looks at and compares both the Spearman's and the Kendall tau rank correlation coefficients.

Figure 1 shows a graphic presentation of the application of the above-mentioned procedure. The procedure is based on the division of the structure into individual sections. Within these sections, LHS is used to generate random numbers for the various basic variables (e.g. modulus of elasticity) from assumed distributions. For every set of simulated basic variables a calculation run of the underlying FE model is performed and the system response is determined.

The determination of the system response (e.g. natural frequency or maximum deflection) is performed at an arbitrary point in the system which may, for example, correspond to a monitoring point. Upon termination of the simulation processes the results of each run are compared by correlation with the simulated basic variables of every run.

This procedure (compare with Figure 1) provides a correlation of the varied basic variable (e.g. modulus of elasticity) and the system response at the selected point (e.g. monitoring point).

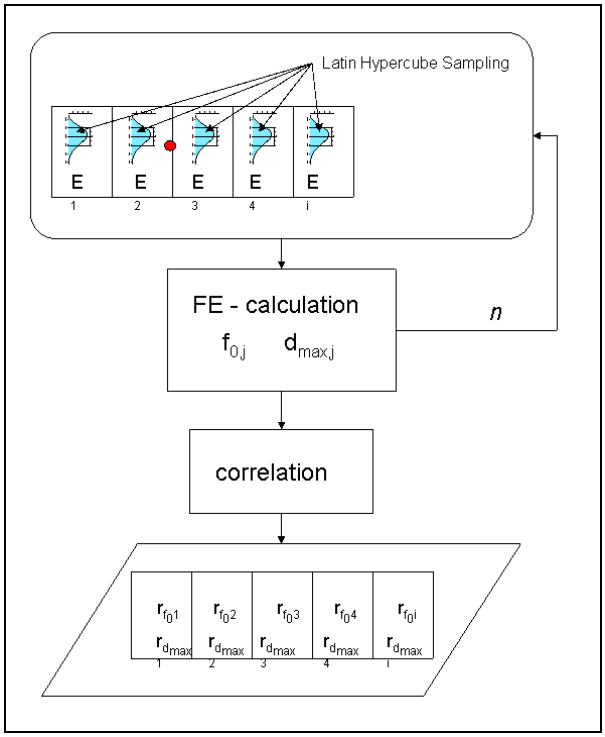

Figure: 1: Flowchart of objective procedure

5 EXAMPLE OF APPLICATION

5.1 Bridge in Zeiselmauer (Lower Austria)

The analysed bridge is located on the Franz-Josefs-Bahn railway line at kilometre 24.985 in the cadastral municipality of Zeiselmauer (Lower Austria). The bridge is a 3-span continous made of reinforced concrete. The two outer sections are 7m long, the middle section is 8m long.

The track slab of the bridge is between 0.5m and 0.55m thick. According to the planners B400 concrete was used in the construction. The crossing-angle of the structure is 85°, resulting in slope distances between supports of 7.8m – 8.7m – 7.8m (shown in Figure 3).

The bridge's elastomeric bearings are movable in all directions. In addition, horizontal-load steel bearings were arranged both fixed transversely and longitudinally as well as fixed transversely only.

The measurements on the bridge were accomplished in 2007 within a period of about 7 months permanently. The measurements include acceleration, deflection and temperature measurements. The Figure 4 shows the distributions for the vertical deflection and for the 1st eigenfrequency.

Figure 2: Pictures of railway bridge in Zeiselmauer (Lower Austria)

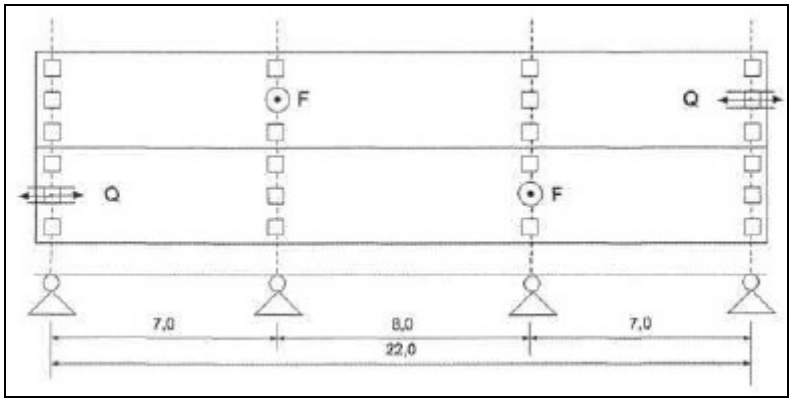

Figure 3: Static system of the bridge in Zeiselmauer (Lower Austria)

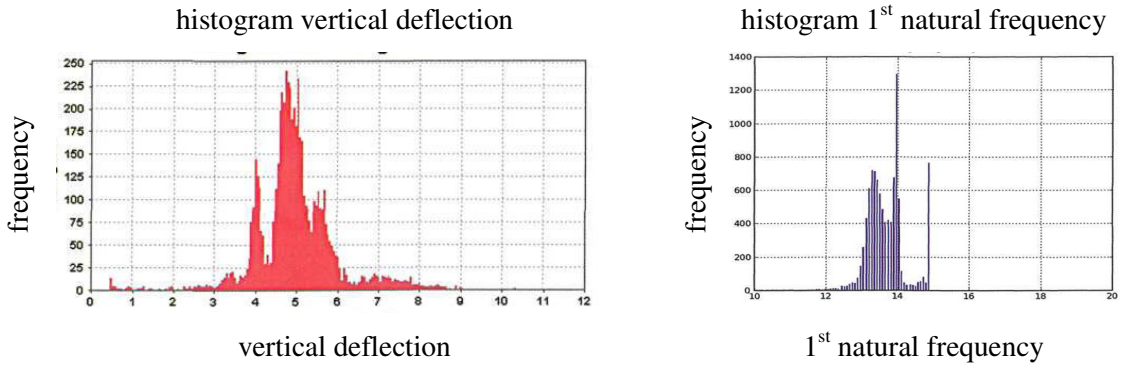

Figure 4: Measurement results of the long term monitoring at the bridge in Zeiselmauer

The figure 5 shows the Finite Element (FE) model of the analysed bridge which served as the basis for further analyses. The parameters for the model are based on the measurement results shown in figure 4. The subsequent calculations were performed on the basis of only one of the two bridge sections. In order to ensure that the model was as realistic as possible the roadbed (gravel roadbed) and tracks were integrated into the model. The multicoloured elements on the bridge-slab are those areas for which a simulation analysis was performed. At the red measuring points the response of the structure was determined.

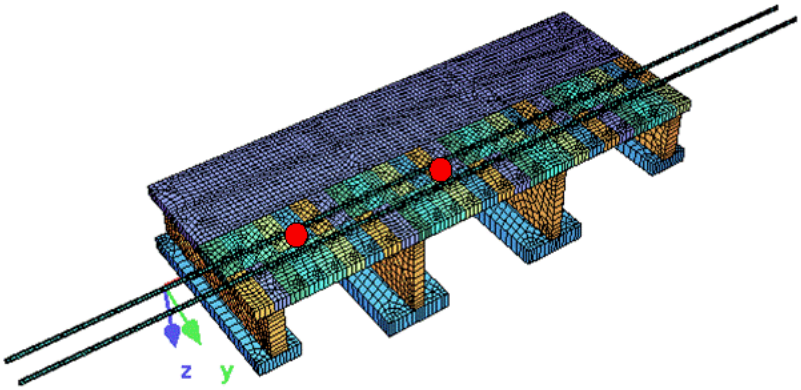

Figure 5: Finite Element model of the bridge in Zeiselmauer

5.2 Simulation parameters

5.2.1 Basic variable

The modulus of elasticity served as the basic variable for the simulation. It was defined as 35000 N/mm^2, corresponding to the B400 concrete type used in the slab. This value was assumed to be the average value in a log-normal distribution. The covariance of the distribution was assumed to be between 0.02, 0.05, 0.10, 0.15 and 0.20.

For calculation purposes a total of 40 samples were generated.

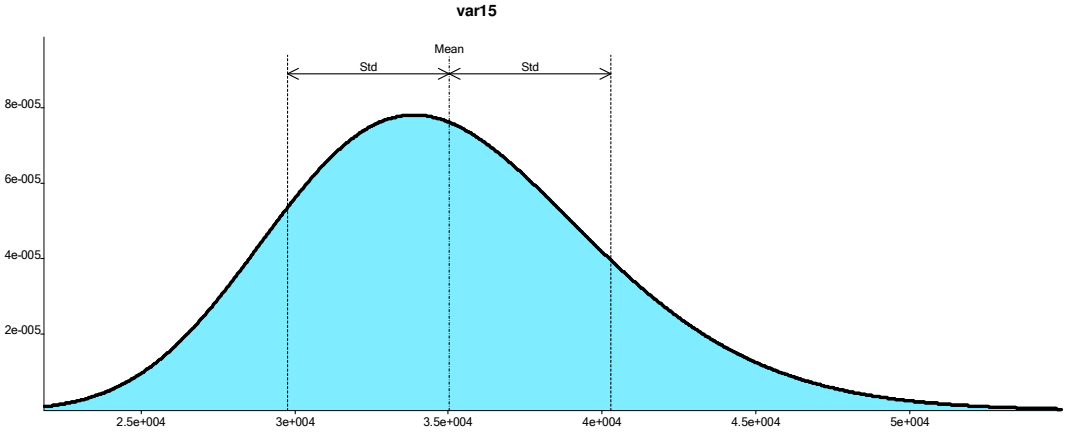

Figure 6: Log-normal distribution for elasticity modul mean 35000 N/mm^2, covariance 0.15

5.2.2 Response of the structure

In order to describe the response of the structure the time response for acceleration and the deflection at the two measuring points were recorded. The actual parameters used to identify the response of the structure were the 1st natural frequency and the maximum deflection.

The 1st natural frequency was determined through a frequency analysis (using FFT) of the acceleration decay of the bridge.

The structure was loaded by means of a simulated train passage. Figure 7 shows the arrangement of the loads. A 4-axle goods wagon with a load of 250kN per axle divided between 2 tracks was used in the simulation. The speed of the load passage was set at 25 m/s which roughly corresponds to the maximum speed allowed in this section.

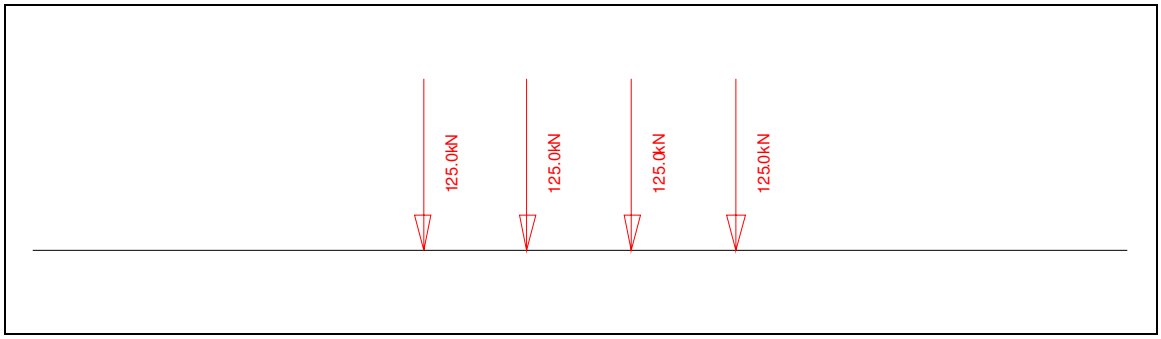

Figure 7: Load cases for the simulation

5.3 Simulation result

Figure 8 illustrates the result of the simulation calculation for a covariance of 0.15 and shows the correlation coefficient (according to Kendall tau and Spearman) for the natural frequency as well as for the maximum deflection resulting from a train passage. The blue circles represent the measuring point on the structure; the blue dotted lines represent the bearings.

The results show that, depending on the selected measuring points, areas of increased correlation can be identified. These areas on the structure exhibit an increased impact on the appropriate measuring point if the stiffness is changed.

Looking at the 1st natural frequency for the measuring point in the outer section of the structure we can see that increased correlation occurs in the section of the structure where the measuring point is located as well as in the middle section of the structure. The results for the measuring point in the middle section of the structure show that increased correlation occurred mainly in the middle section. Taking into account Spearman r, increased correlation also occurred in the two outer sections of the structure.

Looking at the maximum deflection at the measuring point the results are very different from those found for the 1st natural frequency. The results show that areas of increased correlation mainly occur in those structures for which the measuring point was analysed. This behaviour becomes particularly apparent when looking at the correlation coefficient according to Kendall tau.

All in all, the correlation data established according to Spearman are generally higher than those established according to Kendall tau.

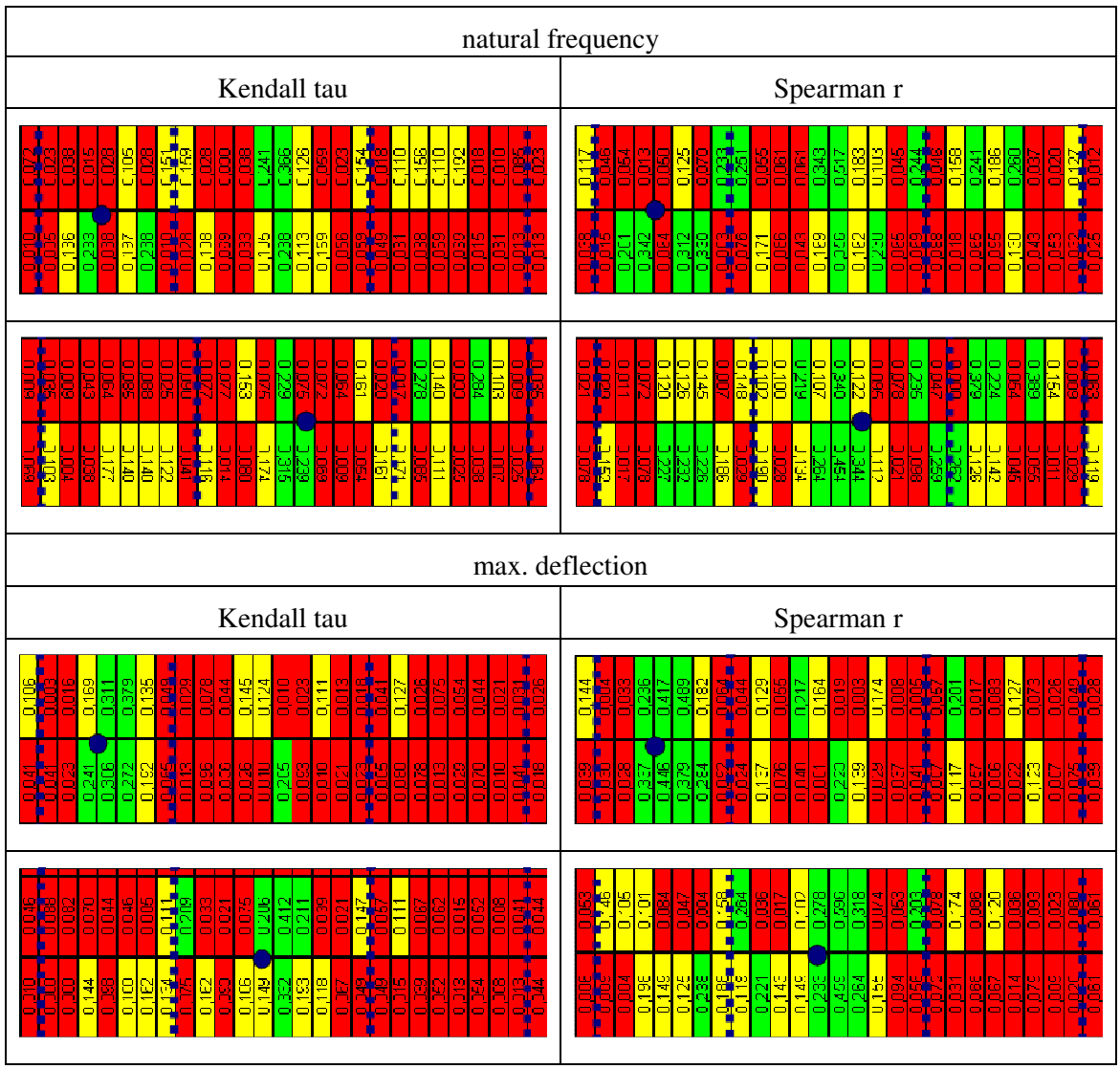

Figure 8: correlation result for the present simulation

6 CONCLUSION

The present article shows a numerical based method to optimize the position an the amount of sensors to determine a specific behaviour of a structure.

A relatively simple simulation procedure allows for the positioning of measuring points in such a way that impacts at certain sections of the structure can be reproduced with a maximum degree of significance.

However, the simulation results demonstrate the problems arising from system identification (damage identification in particular) by means of indirect measurements such as acceleration measurements, a finding clearly indicated by the consistently low correlation coefficient.

For complex structures, this procedure provides relatively simple means for identifying the position as well as the number of measuring points needed to ensure that specific damage can be reflected with a maximum degree of significance.

Also, this procedure enables the user to determine the indicator of the structure response to which a specific damage pattern reacts well.

7 PROSPECTS

One possible extension of the above-presented procedure is its combination with an optimization algorithm. Such an optimisation would maximise the various determined correlation coefficients by providing a suitable selection of measuring points.

The resulting procedure could be applied to identify the lowest possible number of ideal measuring points for certain types of damage to (load-bearing) structures.

8 REFERENCES

Handel, C. 2007. *Richtlinie für dynamische Messungen an Eisenbahnbrücken*

SOFISTIK. *Sofistik Handbuch Version 2*“, Sofistik AG Oberschleißheim, Deutschland 2008

UIC Guidelines für Railway Bridges: *Dynamic Measurements and Calculations*, Bridcap Project Team G776x-2006, ISBN 2-7461-1235-3, Railway Technical Publications, Paris 2007.

Peeters, B.: *System identification and damage detection in civil engineering*. PhD thesis, Department of Civil Engineering, Katholieke Universiteit Leuven, 2000.

DeRoeck, G, Peeters, B. and Maeck, f.: *Damage identification on the Z24 bridge using Vibration monitoring*. Smart Mater. Struct. 10, 2001, S. 512-517.

R. Geier, M. Österreicher, M. Pircher, Langzeitmessungen an einer Eisenbahnbrücke, Beton- und Stahlbetonbau 6/2008.