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Eccomas Proceedia COMPDYN (2017) 2705-2718

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COMPDYN 2017
6th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, M. Fragiadakis (eds.)
Rhodes Island, Greece, 15–17 June, 2017

MICROWAVE INTERFEROMETRY MEASUREMENTS FOR RAILWAY-SPECIFIC APPLICATIONS

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Keywords: microwave interferometry, dynamic measurements, railway bridge dynamics

Abstract. *The microwave interferometry is a rather new measurement method, whose functioning principle allows the non-contact synchronous acquisition of structural displacements for several points along a structure, with accuracy in sub-millimetre range at a sampling rate of up to 4 kHz. Due to the high sampling rate, the acquisition of dynamic responses is also possible. Hence, main modal structural parameters such as natural frequencies and damping ratios can be straightforwardly identified. Furthermore, the synchronous measurement of several points along the targeted object, achieved due to a range resolution of about 0.75 m, may allow the direct determination of modal shapes. Under consideration of its novel character and a lack of previous experience with respect to railway-specific tasks, the measurement method had to be subjected to a systematic and comprehensive validation process prior to a reliable implementation in everyday practice. The validation process included several parallel measurements and comparisons with conventional measurement techniques. Besides the direct verification of the quality of the results, it was used as well for defining boundary conditions and limitations of the measurement method with respect to railway-specific applications. As a result, an evaluation matrix was created, which illustrates the applicability of the microwave interferometry for different types of structures. This paper gives a brief introduction of the microwave interferometry and presents some aspects and selected results of the validation process, which was performed within a cooperation project between the TU Darmstadt (Germany) and the German Railways (Deutsche Bahn AG).*

Peer-review under responsibility of the organizing committee of COMPDYN 2017.
doi: 10.7712/120117.5600.17334

1 INTRODUCTION

In the actual context of an ageing infrastructure in the railway sector and a rapid development of modern, faster and heavier vehicles with innovative axle arrangements, the reassessment of existing bridges becomes an ever more challenging task for civil engineers. Standard methods for reassessment of existing structures involve in a first instance a numerical analysis, whose level of detail can be varied according to the complexity of the structure and to the required accuracy of the results [1]. However, if the numerical analysis reveals an exceedance of the limit values with respect to the structural capacity or serviceability of the structure, measurements of the real dynamical structural behaviour are required in order to provide a realistic basis for updating the numerical models considered in the structural analysis [1]. This last step is necessary, as the modal parameters obtained through experimental investigations might differ significantly from the parameters resulting from the structural analysis. Such differences occur mostly due to different assumptions, simplifications and uncertainties within the structural model [2, 3]. In that regard, the German Railways (Deutsche Bahn AG) currently carries out a very elaborate reassessment project, which deals with the investigation of the dynamic compatibility of bridges located across the entire German railway network. It was motivated by the introduction of the new high-speed train ICE 4, whose carriage lengths lie outside of the validity range of the high speed load models for dynamic analysis (HSLM) specified in [4, 5]. Besides a significant number of experimental investigations, the reassessment project implies automated numerical analyses of bridge structures as well as comprehensive parametrical studies.

The substantial demand for dynamic measurements over the last decades represented also an optimal condition for technological progress in relation to measurement technologies in civil engineering, which indicates a clear trend towards non-contact, easy-to-use techniques. Among those, the microwave interferometry (MI) represents a rather new measurement method, whose functioning principle allows the non-contact synchronous measurement of structural deflections of several points along a structure, achieving a sub-millimetre accuracy level at a sampling rate of up to 4 kHz. Due to the high sampling rate, dynamic structural responses can also be captured and used for the straightforward identification of structural modal parameters. The non-contact character of the microwave interferometry represents a very important aspect, especially in case of railway bridges, as the conventional methods require high labour efforts, e.g sensors have to be usually mounted on the measured object, whereas several structures cannot be investigated at all due to bad accessibility.

Due to the novel nature of the microwave interferometry, it had to be subjected to a comprehensive validation process, which focused mainly on comparisons with results of synchronous conventional measurements. Section 2 of this paper gives a brief introduction of the microwave interferometry while the main findings of the validation process are presented in Section 3. Conclusions are drawn in Section 4.

2 MICROWAVE INTERFEROMETRY

The MI radar device (microwave interferometer) is mounted on a tripod and emits electromagnetic waves, which are reflected by discontinuities of the target objects lying within the antenna beam. The functioning principle of the microwave interferometry is based on the acquisition of amplitude and phase of the backscattered signal [6].

The object displacement Δr within a sampling interval can be expressed in dependency of the corresponding phase change ϕ and the wavelength λ of the emitted microwaves according

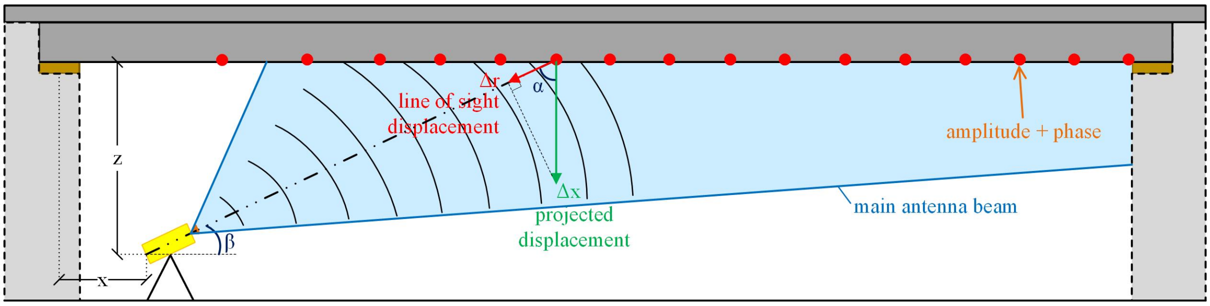

Figure 1: Typical MI measurement situation for bridges (the red dots represent the centres of the resolution cells)

to equation 1.

$$\Delta r = -\frac{\lambda}{4 \cdot \pi} \cdot \phi \tag{1}$$

The interferometric phase ϕ can be determined as a function of several influence factors according to equation 2.

$$\phi = \phi_{\text{disp}} + \phi_{\text{atm}} + \phi_{\text{noise}} \pm 2\pi n \tag{2}$$

Here ϕ_{disp} corresponds to the phase difference resulting from movements of the targeted reflecting objects along the line of sight, ϕ_{atm} depicts the phase shift caused by atmospheric effects and ϕ_{noise} represents the measurement noise. However, the short time measurements (typical for investigations in structural dynamics) are usually characterised by insignificant atmospheric changes. The corresponding term ϕ_{atm} in equation 2 can thus be mostly neglected. The term $2\pi n$ indicates the wrapping of the interferometric phase between $-\pi$ and $+\pi$, corresponding to $-\lambda/4$ to $\lambda/4$ due to the double travelled distance, while n represents the phase ambiguity, since only a phase difference can be measured and not the integer number of phase cycles. It can be solved under different assumptions. For example, regarding the displacement of a bridge structure, it can be assumed that it does not exceed a quarter of the wavelength within one sampling interval, i.e. $n = 1$ ($\pm\lambda/4 = \pm 4.4$ mm, $\lambda = 17.4$ mm). Considering an acquisition rate of 200 Hz , a displacement of about 880 mm within one second would still be measurable. This value obviously lies outside the plausible range for regular bridge structures.

Figure 1 shows a typical measurement situation for bridge investigations. It is to be noted, that the microwave interferometers in RAR mode (Real Aperture Radar, suitable for dynamic signal acquisition) can measure only one-dimensional displacements Δr, i.e. in the line of sight of the device. It is to be subsequently projected with respect to the assumed direction of movement Δx according to equation 3 and figure 1. Hence a good understanding of the mechanics of the structure is required in order to make realistic assumptions regarding the real direction of movement, which has to be considered when setting up the device.

$$\Delta x = \frac{\Delta r}{\cos(\alpha)} \tag{3}$$

The amplitude of the backscattered signal is significantly affected by the reflectivity of the targeted objects. In general, a good reflectivity is expected from every discontinuity of the structure, whose dimensions exceed the wavelength λ of the transmitted wave. Concerning the reflectivity of bridges, it was observed that steel structures usually present a better reflectivity than reinforced or prestressed concrete, as the bottom surface of concrete bridges, which is

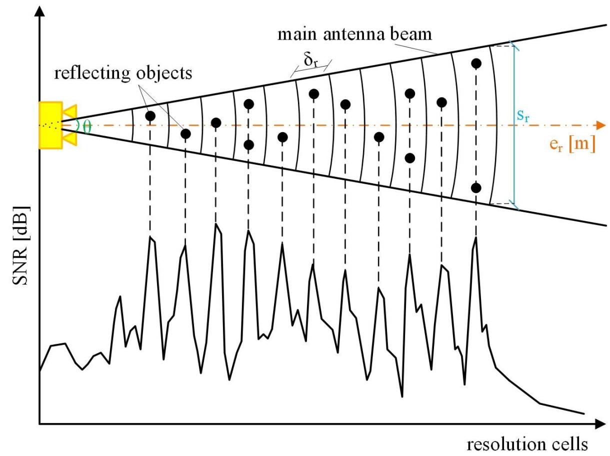

Figure 2: Range resolution cells of a microwave interferometer and corresponding SNR values

illuminated by the antenna beam, is mostly plain. This can lead to a dominant forward reflection of the microwaves and so to a loss of intensity of the backscattered signal [7]. Therefore it is recommended to check the quality of the reflected signal prior to the subsequent analysis. This can be done by means of the signal-to-noise ratio and of the complex representation of signal (polar plot) [8].

Microwave interferometers employ the stepped frequency continuous wave (SFCW) [9] or the frequency modulated continuous wave (FMCW) [10] principle in order ro achieve the range resolution, which can be expressed in dependency of the bandwidth B of the transmitted wave and of the speed of light c according to equation 4. Assuming the maximum bandwidth of $200\ \mathrm{MHz}$ allowed by the German Federal Network Agency, the corresponding range resolution δ_r is determined to be $0.75\ \mathrm{m}$.

$$\delta_\mathrm{r} = \frac{c}{2 \cdot B} \tag{4}$$

A possible drawback of the microwave technology is represented by the fact that the microwave interferometers deliver a weighted average of the echoes for every resolution cell. This means that the movements of different reflecting targets situated in the same resolution cell cannot be distinguished (figure 2). However, this effect can be avoided in many situations by choosing a proper position of the MI radar, so that each cell contains only one dominant reflector. An useful mean for this task is the rough estimation of the width s_r of the antenna beam over the distance e_r, which can be done according to equation 5 (see also figure 2), whereas θ depicts the horizontal opening angle of the antenna beam.

$$s_\mathrm{r} = 2 \cdot e_\mathrm{r} \cdot \tan\left(\frac{\theta}{2}\right) \tag{5}$$

A more detailed overview of the microwave interferometry is given in [6, 8, 11] while several application examples are presented in [12, 13, 14].

3 VALIDATION PROCEDURE

3.1 General

The validation process was carried out within the framework of a project initiated by the TU Darmstadt and the German Railways. One of its main aims was to verify the applicability of the microwave interferometry for regular dynamic measurements of railway bridges. The formulation of boundary conditions and possible limitations of the measurement method was also intended. The procedure included, among others, several simultaneous measurements with conventional systems with the purpose to compare the MI results and the results of the conventional measurements, whereas the latter were considered to be accurate and therefore served as reference for all the comparisons. The primary focus of the investigation was set on the determination of natural frequencies and corresponding damping ratios, as usual dynamic measurements of railway bridges refer to these quantities, which are mostly needed in the model updating process. The verification of the values for the absolute displacements served only as a secondary aim within the actual phase of the project.

Before proceeding to the measurements of railway bridges in operation, several laboratory tests were carried out at the TU Darmstadt. They implied measurements of a simple supported steel beam with span length of 8 meters, installed 6.8 meters above ground level, in order to simulate real measurements situations for bridges. The results were very satisfactory [15].

A total of 18 structures have been investigated by microwave interferometry within the in situ validation process of railway bridges (see table 1). For 13 of them, parallel conventional measurements could be carried out (no. 6 to no. 18 in table 1). The conventional measurements were mostly performed by measurement teams of the German Railways. Therefore the standard

No.	Bridge	Location	Type	Route no.	km
1	Muhr am See	Muhr am See	filler beam deck	5321	29.39
2	Große Sude	Hagenow	prestressed concrete slab	6100	189.49
3	Fornbachtal	Coburg	prestressed concrete girder	5919	111.40
4	Deutschherrnknai	Frankfurt a. M.	girder grid (steel)	3660	1.58
5	Schmutter	Augsburg	box girder (steel)	5302	17.32
6	Garather Bach	Düsseldorf	plate girder (steel)	2650	25.17
7	Hauptstraße	Laatzen	plate girder (steel)	1733	8.46
8	Elbe-Lübeck-Kanal	Büchen	tied arch (steel)	6100	238.26
9	Oesterholzstraße	Dortmund	rigid frame (steel)	2650	120.89
10	Am Kupferstrange	Hildesheim	prestressed concrete girder	1770	42.62
11	Flanitz	Klingenbrunn	plate girder (steel)	5821	15.42
12	Scheidestraße	Hannover	rigid frame (reinforced concrete)	1730	3.20
13	Kinzig	Offenburg	tied arch (steel)	4000	147.71
14	Zusam	Donauwörth	box girder (steel)	5300	39.79
15	Siebentischstraße	Augsburg	girder grid (steel)	5503	59.08
16	Altmühl	Dietfurt im Mittelfranken	plate girder (steel)	5501	133.29
17	Durlacher Allee	Karlsruhe	continuous plate girder (steel)	4020	57.72
18	Apfelstädt	Neudietendorf	box girder (steel)	6298	1.29

Table 1: Structures investigated by microwave interferometry

evaluation parameters and methods prescribed for their investigations were adopted also for the analysis of the MI measurements, in order to facilitate the comparison process. The analysis method is described in detail in [8, 12].

The conventional measurements were performed employing linear variable displacement transducers (LVDT) and/or conventional acceleration sensors. However, in several situations, the local circumstances (e.g heavy traffic under the bridge or bridges over rivers) did not allow the installation of LVDTs as they require a fixed reference point directly underneath the point of interest. In these cases, the comparisons with regard to the modal parameters were carried out using acceleration data. Direct comparisons of absolute values are then possible only on acceleration level, using the second derivative of the displacement.

3.2 Example

The railway bridge *Garather Bach* (figure 3) is situated in Germany, at km 25.17 of the railway route no. 2650 (Köln-Duisburg). From a statical point of view, the bridge consists of two simply suported, uncoupled steel plate girders (denoted as TBW 1 and TBW 2 in figure 4). Figure 4 shows the complete measurement layout of the investigation, which implied both measurements with and without corner reflectors. The corner reflectors were installed only on TBW 1 in the very proximity of the conventional sensors, in order to secure unique dominant signals from the MI resolution cells including the measurement points MP 1 and MP 2. In the following, only results from the first measurement set-up (TBW 1) will be presented, as the results of the comparisons from the second set-up (presented in [13]), which is very similar to set-up 1 (corner reflectors are missing), are very consistent, revealing similar agreement between the different type of sensors as in the first set-up. The following comparisons refer

Figure 3: Railway bridge *Garather Bach* (Düsseldorf, Germany)

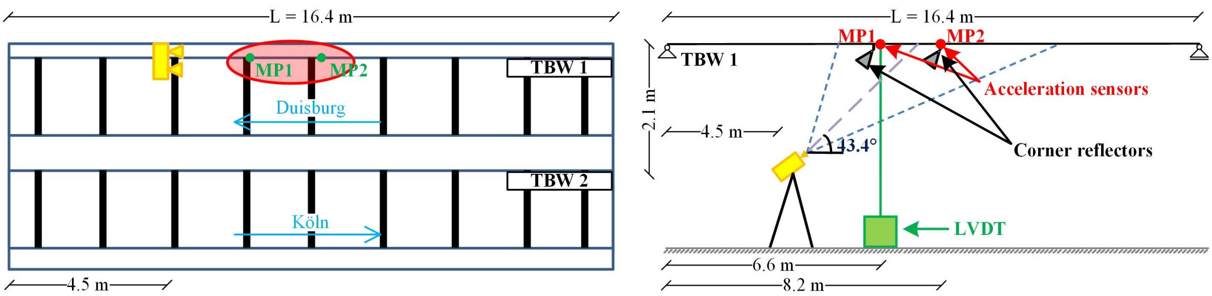

Figure 4: Measurement layout *Garather Bach*: top view (left) and side view (right)

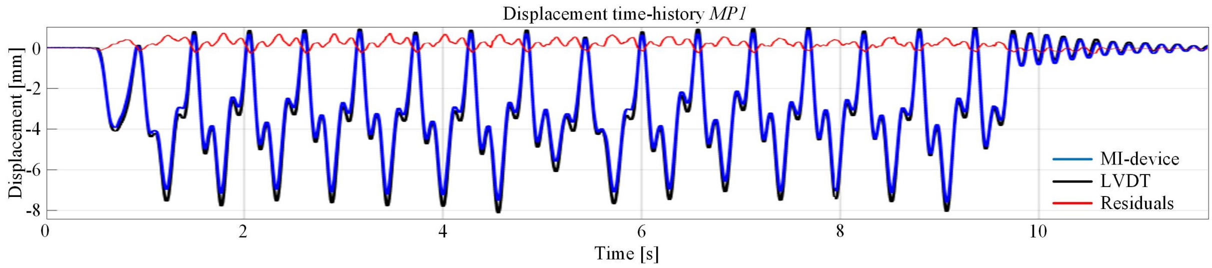

Figure 5: Displacement time series measured with a microwave interferometer and a conventional sensor at MP 1

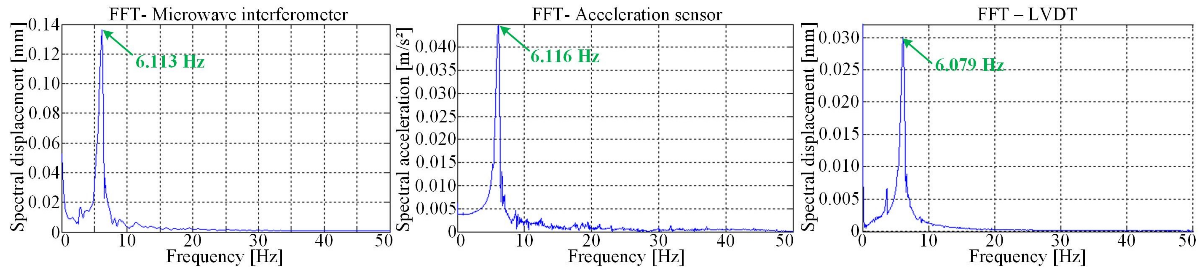

Figure 6: Frequency spectra resulting from the analysis of all employed systems

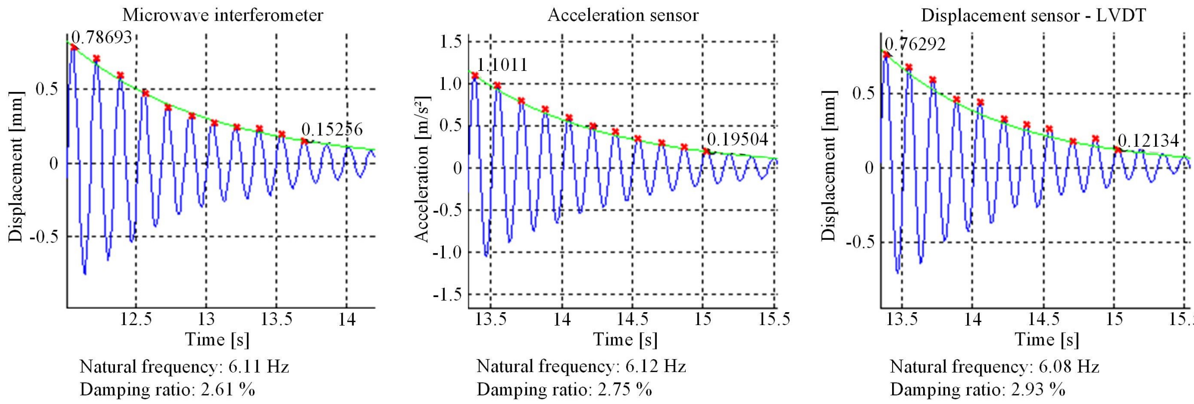

Figure 7: Estimation of the damping ratio with signals from all the measurement sensores used

always to MP 1 and MP 2. However, is to be noted that the results related to the microwave interferometry do not represent the discrete points MP 1 and MP 2, but the resolution cells over a length of 0.75 m including them.

Figure 5 exemplifies the displacement time history generated by the passage of an ICE 3 train (14:27, see table 2) recorded with the MI radar and with a LVDT. The corresponding residuals are represented as well. Table 2 gives an overview over the maximal displacements of MP 1 for all the five passages recorded as well as the corresponding differences between the values of MI and LVDT. Under consideration of the fact that the displacement delivered by the microwave interferometer represents an integral over all the reflectors in a resolution cell and not of a single discrete point considered in the comparison, the results can be classified as quite satisfactory. However, the intended accuracy of 3% has not been yet achieved.

The comparison of the first natural frequency determined using the data from all the three types of sensors revealed a very good correlation of the results. This can be clearly seen in figure 6, which illustrates the frequency spectra determined from all the sensor data for the train

Train passage	Time	Maximal displacement [mm]		
		MI radar	LVDT	Difference MI - LVDT
IC	14:09	7.15	7.89	-0.74
ICE 3	14:15	6.06	6.57	-0.51
RE	14:18	7.12	7.85	-0.73
ICE 3	14:27	7.61	8.14	-0.53
ICE 3	14:31	7.47	8.13	-0.66
Average value				-0.63
Standard deviation				0.10

Table 2: Maximal displacements at MP 1

Train passage	Time	1st natural frequency [Hz]			1st damping ratio [%]		
		MI radar	LVDT	acc. sensor	MI radar	LVDT	acc. sensor
IC	14:09	6.72	6.68	6.72	no clear decay phase		
ICE 3	14:15	6.36	6.46	6.46	2.50	2.39	2.04
RE	14:18	6.36	6.34	6.37	2.67	2.53	2.60
ICE 3	14:27	6.11	6.08	6.12	2.59	2.86	2.63
ICE 3	14:31	6.11	6.12	6.13	2.53	3.10	2.71
Average value		6.33	6.34	6.36	2.57	2.72	2.49
Standard deviation		0.25	0.25	0.25	0.08	0.32	0.31

Table 3: First natural frequencies and the corresponding modal damping ratios (evaluated at MP 1)

passage represented in figure 5. The overview of the corresponding results for all the recorded passages (table 3) confirms the very good accuracy of the MI measurements with respect to the natural frequency estimation.

Figure 7 illustrates the damping estimation for the same train passage displayed in figure 5 using the logarithmic decrement approach [16]. As it can be seen, the estimations using data from the different types of sensors correspond well. The result of this comparison is consistent with the corresponding results for the rest of the passages, which are given in table 3.

3.3 Summary of the results and particular findings

3.3.1 General

As already mentioned in the previous section, the investigations focused mainly on the validation of the analysis concerning the natural frequencies and their corresponding modal damping ratios. The overview of the results and some complementary aspects are presented in the following. It is to be mentioned that the following summary of results refer to only 11 out of 13 synchronous measurements, which could be analysed until the time of composing the present paper.

3.3.2 Natural frequencies

Table 4 gives a summary of the results for all of the investigated bridges. As it can be seen, the first natural frequencies obtained through analysis of the MI data are in a good agreement

No.	Bridge	1st natural frequency [Hz]			1st damping ratio [%]		
		MI	Conv.	Diff. [%]	MI	Conv.	Diff. [%]
1	Garather Bach	6.33	6.36	-0.47	2.57	2.49	+3.11
2	Hauptstraße	3.89	3.90	-0.26	1.29	1.50	-16.28
3	Elbe-Lübeck-Kanal	2.73	2.73	0.00	-	-	-
4	Oesterholzstraße	4.83	4.81	+0.41	-	-	-
5	Am Kupferstrange	4.26	4.31	-1.17	1.59	1.67	-5.03
6	Scheidestraße	8.06	7.99	+0.86	-	0.94	-
7	Kinzig	1.75	1.75	0.00	-	-	-
8	Zusam	6.55	6.47	+1.22	-	0.95	-
9	Siebentischstraße	4.82	4.65	+3.53	1.61	1.51	+6.21
10	Altmühl	6.96	6.85	+1.58	1.07	0.99	+7.48
11	Durlacher Allee	5.51	5.51	0.00	0.84	0.72	+14.29

Table 4: Results summary of the validation measurements

with the corresponding results from conventional measurements, showing percentage differences of up to 3-4%.

It can be stated that the natural frequencies are the quantities which could be determined robustly and accurately in all the investigated cases. However, in order to allow a computation of the natural frequencies, it is required that they are properly excited. This condition is practically always fulfilled for the first natural frequency of beam-like bridges. In contrast, natural frequencies of higher modes could be determined only in some isolated cases (using MI data) and are therefore not explicitly mentioned in the comparison. The reason for this is that the higher frequencies are usually not adequately excited by normal train passages, since the excitation frequencies at regular travel speeds lie below 10 Hz. This value is by far lower than usual second and third natural frequencies of railway bridges. Furthermore, the authors encountered cases in which higher natural frequencies could be determined from acceleration data but not from MI displacement measurements. This effect, which is not explicitly related to the microwave interferometry principle, occurs due to the proportionality between acceleration and displacement in the free vibration phase with the negative square of the angular frequency as a proportionality constant. This leads to higher, measurable amplitudes in the upper range of the acceleration spectrum.

The MI experience gathered so far shows that concrete bridges present usually lower displacement amplitudes as steel bridges in the free vibration phase due to their higher stiffness and mass distribution. Thus one should expect successful determination of higher natural frequencies of concrete bridges only in exceptional cases.

3.3.3 Damping ratios

Regarding the modal damping ratios, the comparisons between the MI and the conventional systems revealed as well differences lying in an acceptable range (0-16%, s. table 4). In general, the determination of modal damping ratios from MI data can succeed independently of the structure type as long as the analysed data series present a clear decay trend in the free vibration phase (after train passage) of the analysed modes. The individual modes can be isolated, for example, by bandpass filtering of the signal used for the determination of natural frequencies. For the damping estimation, it is recommended to consider only displacement amplitudes which are significantly higher than the device accuracy specified by the manufacturer, e.g. $0.01\ \mathrm{mm}$ (in laboratory conditions) for the microwave interferometer IBIS-S manufactured by IDS - Ingineria del Sistemi S.p.A. [17].

Within the present investigation, the axle arrangement and the travel speed of the trains (i.e. the excitation frequency) could be identified as main influence factors responsible for generating evaluable decay processes. Pronounced dynamic effects and thus considerable displacement amplitudes in the decay phase are expected in case the excitation frequency lies close to one of the natural frequencies of the structure. The structure type only plays a subordinate role. However, the previous experience showed that concrete bridges present suitable decay amplitudes only in sporadic cases due to their higher stiffness, mass and damping ratios.

Furthermore, damping ratios of higher modes could be determined only in some isolated cases. The reason for this is usually, as mentioned above, the discrepancy between the excitation frequencies and the higher natural frequencies of the structure, which does not facilitate the occurrence of significant dynamic effects (i.e. proper displacement amplitudes) in the higher modes.

3.3.4 Absolute displacements

Although the accuracy of the displacements achieved within the few measurements of railway bridges in operation performed with parallel LVDTs lies in a satisfactory sub-millimetre range, the validation of the absolute displacements requires further investigations since the accuracy level of 3% intended by the authors has not been reached yet.

One of the main issues the MI users have to consider is the exact identification of the dominant reflector in each resolution cell, as the elevation angle β of the MI radar and the vertical distance z from the zero reference point of the MI device to the reflecting point of the structure (s. figure 1) are the quantities used in the projection of the line of sight movement to the vertical displacement. Slight errors in the input of vertical distances lead to erroneous projection of the displacement. This effect should be paid attention to, especially in case steel bridges presenting visible cross beams at the bottom side. This is clearly illustrated in figure 8 on the example of a tied arch bridge. As it can be seen, the difference between the vertical displacements obtained by projecting the line of sight displacement with respect to the upper edge of the cross beam (distance z_1) and to the lower edge of the cross beam (distance z_2) can be considerable. In comparison with the conventionally measured vertical displacement, the consideration of z_1 as

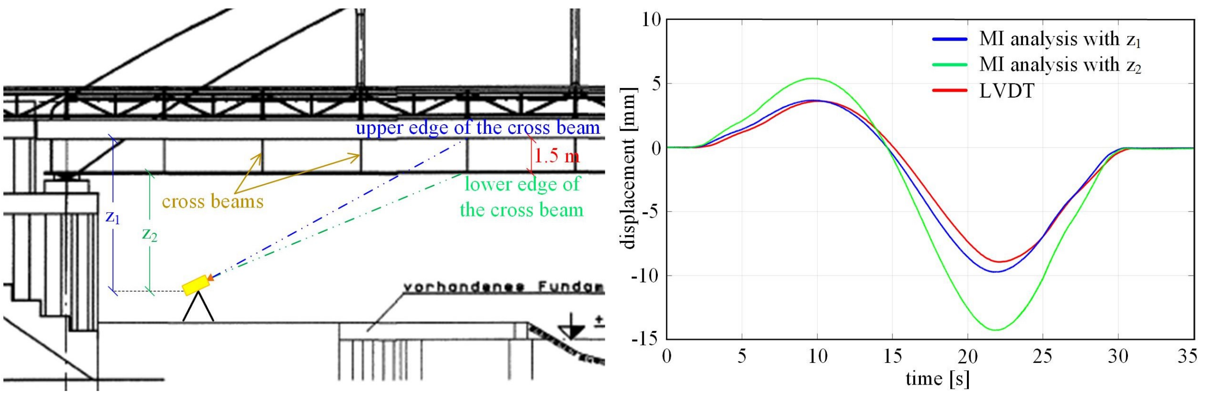

Figure 8: Sketch of a measurement set-up for a tied arch bridge (left) and analysis of vertical displacement considering two different reference points with the heights z_1 and z_2 respectively for the vertical coordinate of the MI device (right)

distance to the reference reflecting point delivers appropriate results. The reason for this is the reflectivity of the joint cross beam-bridge deck (at the upper flange of the cross beam), which is significantly higher than the reflectivity at the lower flange.

Another problem which has to be considered within the analysis of vertical displacements refers to the broadening of the antenna beam. Due to the increasing width of the beam over the distance, the distant resolution cells might contain several reflectors with different movement behaviour (s. figure 2). The resulting displacement in this case represents an integral over the movements of all the reflectors lying in the specific resolution cell, whereas the weighting factor of the different reflectors can not be determined. Therefore it is recommended to install the MI devices as close as possible to the points of interest, so that they fall in closer resolution cells with reasonable widths.

Furthermore it is to be noted that the analysis of MI measurements assumes pure vertical (e.g. in case of bridges) or pure horizontal (e.g. noise insulation walls) displacements of the measured object with respect to the vertical plane which includes the line of sight of the device. In both cases, the angle which has to be considered in the projection of the line of sight displacement is the angle between the line of sight and the assumed movement direction. Measurement set-ups with expected movements in both directions are to be avoided, as the individual components can not be separated.

3.3.5 Mode shapes

The fulfilment of the quality criteria (signal-to-noise ratio and polar plot) for several resolution cells along the structure is a necessary condition for the determination of modal shapes using MI data. Furthermore, suitable displacement amplitudes in the investigated mode are required. On that account, an analysis of mode shapes is rather possible in case of steel structures which mostly present several constructive elements with good reflectivity at the bottom side (e.g. cross beams). In addition, the displacement in the free vibrations phase are expected to be higher in case of steel bridges than for concrete structures due to the different mass, stiffness and damping parameters. Within the previous investigations only few structures (exclusively steel) allowed a clear determination of the mode shapes.

Figure 9 exemplary shows the first two mode shapes of a continuous beam bridge (no. 7 in table 1, two spans à 21.13 m) obtained using MI data. It is to be noted that the mode shapes determined from MI measurements possess only a qualitative character, especially in case of structures with multiple tracks. This is due to the fact that the width of the antenna beam is

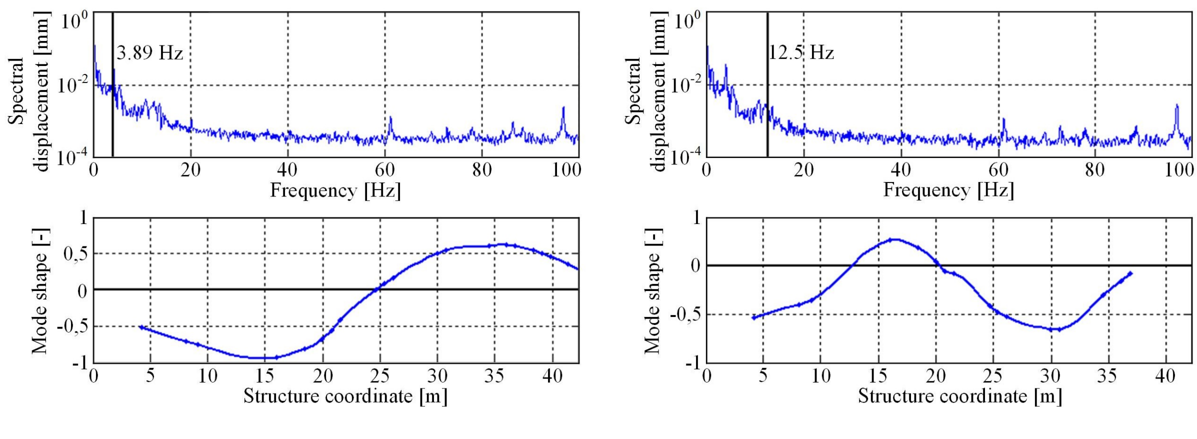

Figure 9: First two mode shapes of a continuous beam bridge from a MI measurement

wider in the distant resolution cells (s. figure 2), which are likely to include additional, unwanted reflecting elements of the structure. Nevertheless, the qualitative determination of mode shapes is very helpful for the correlation of the measured to the computed natural frequencies and mode shapes. It represents a proper tool for the plausibility check of the measurement.

3.4 Evaluation matrix

As a result of the comprehensive investigation, an evaluation matrix was created (s. table 5). It should illustrate the applicability of the microwave interferometry for different types of structures and measurements tasks. For the sake of completeness, the matrix also contains informations about noise insulating walls, which were not addressed explicitly in this paper. However, the cooperation project between the TU Darmstadt and the German Railways included as well experimental investigations on this topic.

Task / Structure type	abs. disp.	natural frequency 1st	natural frequency higher	damping ratios 1st mode	damping ratios higher modes	mode shapes
Girder grid (steel)	+++	+++	++	+++	+	++
Plate girder (steel)	+++	+++	++	+++	+	++
Tied arch (steel)	+++	+++	++	+++	+	++
Rigid frame (steel)	+++	+++	++	+++	+	++
Box girder (steel)	++	++	++	+++	+	+
Concrete bridges	++	++	+	++	-	+
Filler beam deck	++	++	+	++	+	+
Noise insulation walls	+++	+++	++	+++	+	++

Legend: +++ highly suitable, ++ partially suitable, dependent on different influence factors, + suitable only in isolated cases, under certain circumstances, - not suitable

Table 5: Evaluation matrix for judging the applicability of MI for various types of bridges

It should be noted that several factors which are not related to the MI measurement technique underlie the specifications for the natural frequencies and damping ratios of higher modes, such as the previously mentioned lower displacement amplitudes in the higher modes. Furthermore, it is to be mentioned that the evaluation of tied arch bridges refer to the bottom chord (bridge deck girder) and not to the arch itself and that the category of concrete bridges comprises both prestressed and reinforced structures, due to the transferability of the relevant properties.

4 CONCLUSIONS

- A systematic and comprehensive process for the validation of microwave interferometry measurements was conducted within a joint project of the TU Darmstadt and the German Railways.

- The results achieved so far concerning the natural frequencies and damping ratios are generally in a good agreement with reference results of conventional sensors.

- Some complementary aspects which should be considered within the measurement and the subsequent analysis were presented, e.g. possible projection errors occurring due to incorrect identification of the main reflecting points or erroneous results which might occur due to multiple reflectors with different movement behaviours lying in the same resolution cell.

- The comparison of the absolute displacements was only a secondary focus of the investigations. Under consideration of the fact that discrete points are compared to integral displacements over whole resolution cells, the results can be seen as satisfactory (accuracy in sub-millimetre range). However further investigations on this topic are envisaged, in order to achieve an accuracy of 3% (intended by the authors).
- As a result of the comprehensive investigations, an evaluation matrix was created, which illustrates the applicability of microwave interferometry for different structure types and various railway-specific measurement tasks.
- The microwave interferometry can be regarded as a promising technology which can be reliably implemented within the experimental investigations required in the updating process for numerical models of railway bridges.

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