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Vibration measurements in analysis of historical structures

Pomiary i analizy drgań obiektów historycznych

Keywords: Vibrations, Measurement, Analysis, Historical constructions, OMA

Słowa kluczowe: drgania, pomiary, analizy, konstrukcje historyczne, OMA

1. BASIC INFORMATION ON DYNAMIC MEASUREMENTS

1.1. General information

The paper presents contemporary methods of historical structures analyses. These analyses are based on the interrelations among *in situ* dynamic measurements, analysis of the obtained data, and calculation on a FEM model. Thanks to the merging of experimental study with calculation techniques, it becomes possible to perform analyses of valuable historical structures in a way that is safer, more exact and better suited to the real dynamic and static behaviour of the structure. Where the possibilities of theoretical analyses end, experimental studies begin and *vice versa*. Experimental and theoretical models validate each other, which results in a much better customisation of analysis procedures to the studied object and the acquisition of much more precise results, which are simultaneously more reliable and closer to reality. Unfortunately, these studies require the use of very expensive and complex measuring instruments, very expensive and very advanced software and the necessary knowledge and research experience. There are not many scientific research centres in Poland, in Europe or in the world that possess all of the above, but there are some. The Structural Dynamics Division of Civil Engineering Institute of Wrocław University of Technology is one of them.

1.2. System PULSE™ – Brüel & Kjær's platform for vibration analysis

Dynamic measurements were performed with the use of a Brüel & Kjær 34 channel PULSE™ system, (Fig. 1).

The PULSE™ system we use can be divided into two independent parts, each of 17 input channels, all featuring the frequency range of DC to 25.6 kHz and 12 additional auxiliary channels. The separate power supply units enable using 110 – 240 V AC, 10 – 32 V DC, built in batteries, external power packs and portable, petrol driven generators. Being based on type 3560 PULSE system and its Dyn-X acquisition modules, all inputs reach the dynamic range of 160 dB with ideal linearity and phase matching. All of this, together with TEDS technology and the extensive diagnostics of the input chain condition, makes the data acquisition practically unattended, mostly because there is no need to control the input range settings anymore.

Fig. 1. Brüel & Kjær's PULSE system with 34 measure channels

1.2.1. Transducers and accessories for Experimental Modal Analysis (OMA and EMA)

The system has been equipped with transducers (Fig. 2) intended for the purpose of experimental Modal Analysis: a set of 16 seismic accelerometers DeltaTron 8340 (big mass – 775 g, high sensitivity 1000 mV/ms^{-2}) and a set of 32 mini-accelerometers THETASHEAR 4507 8340 (little mass – 4,8 g, lower sensitivity – 100 mV/ms^{-2}), dynamic PCB strain gauge, and a laser vibrometer, equipped with a shooting telescope, (Fig. 2).

In civil engineering, and especially when performing modal analysis, very sensitive accelerometers are needed. Unfortunately, the more sensitive the heavier the accelerometer is – and the more difficult to fit onto elements of the

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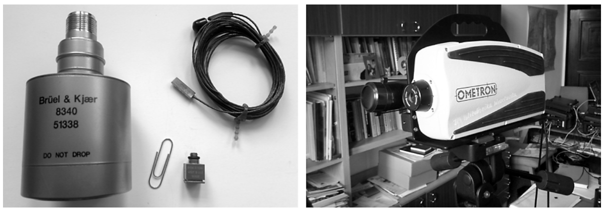

Fig. 2. A seismic accelerometer DeltaTron 8340, mini-accelerometer THETASHEAR 4507, PCB dynamic strain gauge (on the left) and Laser Doppler Vibrometer (on the right)

historical structure. An alternative solution is to use a Laser Doppler Vibrometer, which performs non-contact vibration velocity measurements and can be attached to the PULSE™ system alongside accelerometers and become one of the sensors registering vibration.

1.2.2. *Accessories intended for the purpose of Experimental Modal Analysis*

Additionally, the system has been equipped with accessories intended for the purpose of Experimental Modal Analysis: a small and large impact hammers (Fig. 3), shakers, calibrators etc.

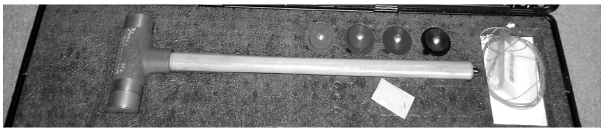

Fig. 3. Large impact hammer (5,448 kg)

1.2.3. *Experimental Operational Modal Analysis (OMA)*

The most important part of the PULSE™ system is the software, which allows to perform complex analyses of vibration. Special attention shall be paid to the Structural Analysis package, covering all kinds of OMA, Operational Deflection Shapes (ODS) and EMA (shaker, hammer) with structural modifications and simulations. The OMA application has been equipped with all of the newest achievements in that field, including automatic search and detection of mode shapes and also automatic detection and removal of harmonic contents in the measured signal.

The OMA package contains 6 algorithms for obtaining eigenfrequencies and eigenforms:

- FDD (Frequency Domain Decomposition)
- EFDD (Enhanced Frequency Domain Decomposition)
- CFDD (Curve-Fit Frequency Domain Decomposition)
- SSI-UPC (Stochastic Subspace Identification-Unweighted Principle Components)
- SSI-PC (Stochastic Subspace Identification-Principle Components)
- SSI-CVA (Stochastic Subspace Identification-Canonical Variate Analysis)

1.3. Simple dynamic analysis

1.3.1. *Time histories*

The typical procedure in simple experimental dynamic analysis is to measure and register the time history of accelerations, velocities or displacements. The exemplary registered time histories of the accelerations are shown in (Fig. 4).

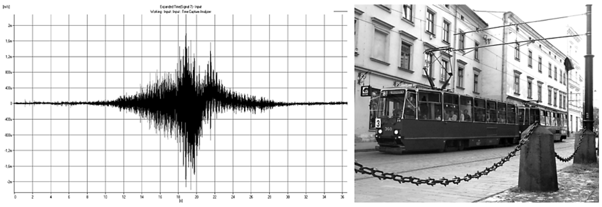

Fig. 4. Exemplary time history of accelerations (passage of a tram, Kraków, Dominikańska Str.)

A measurement taken in order to evaluate the dynamic work of a crack in the Ossolineum library in Wrocław is shown in (Fig. 5).

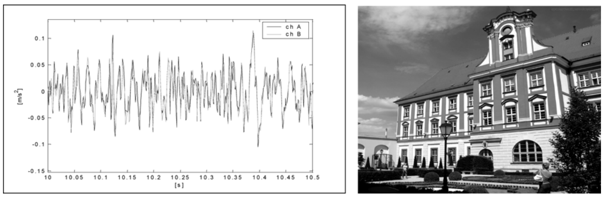

Fig. 5. Exemplary time history of accelerations (on the left) in 2 points on both sides of the crack during the passage of a tram near the Ossolineum library in Wrocław (on the right)

1.3.2. *Spectral analysis*

The classic spectral analysis (FFT) or Autospectrum (Fig. 6) can be performed as a standard procedure in dynamic analysis. These methods make it is possible to extract dominant frequencies in the signal.

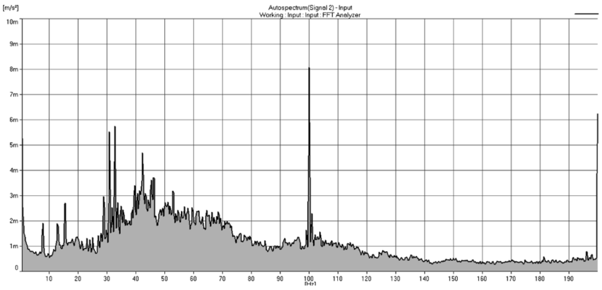

Fig. 6. Exemplary Autospectrum of accelerations (FFT analysis)

1.3.3. *Frequency-time spectrogram*

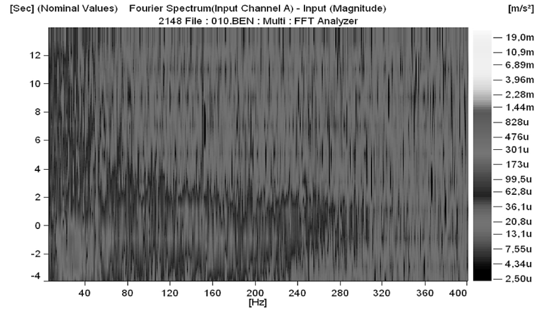

Fig. 7. Exemplary spectrogram of accelerations (frequency-time analysis) of signal shown in (Fig. 4)

The frequency-time analysis (Fig. 7) can also be performed and can be very useful. This analysis makes it possible to observe the changes of the dominant frequencies in time. (Fig. 7) shows a spectrogram of accelerations registered on the wall of the historic building of the Ossolineum library in Wrocław, during the passage of a tram nearby. The figure shows an amplification of the signal, which may be observed with the change of both the time and the frequency domain. The signal is strongest in the frequency range 10-40 Hz.

2. SIMPLIFIED ANALYSIS ACCORDING TO NATIONAL STANDARD

The dynamic loads acting on historical structures are most often due to ground movement. The movement may be caused by traffic (cars, trains, trams, metro) or by seismic or para-seismic excitation. In order to evaluate the structure strain, a full static and dynamic analysis of the structure under a kinematic load may be performed. Such analyses are now performed with the use of FEM. Simplified dynamic analyses are performed by comparing the obtained measurements with given guideline values, which have been determined on the basis of experience of previously observed cases. On a diagram, the placement of the measurement values in reference to these guideline values (above or below the curves of guideline values) indicates how the vibration should be classified. Two instances of dynamic analyses performed according to these guideline values are presented.

2.1. Polish Standard PN-85/B-02170

The Polish standard, entitled *Evaluation of the harmfulness of building vibrations due to ground motion*, allows for the use of simplified analysis in the study of buildings under the following conditions: the buildings must be masonry, with a number of limitations concerning the number of storeys and the dimensions in projection. Two scales have been developed:

- SWD-I for small buildings (max. 2 storeys, the width or length of building less than 15 m).
- SWD-II for larger buildings (up to 5 storeys, whose heights are smaller than the doubled width of the building).

In cases of evaluation performed with the use of the SWD (scale of dynamic influence), the measuring point is placed on the building fundament on the side of the vibration source, or on the bearing wall on the level of the surrounding ground. In this point, two-axis (diaxial) measurements with two horizontal axes are taken.

If the excitation is a harmonic signal, then the excitation frequency and amplitude are determined – the two coordinates of the point whose position on the SWD scale diagrams, compared to the curves for guideline values specified in these diagrams, determines the degree of dynamic harmfulness. However, if the excitation is more complex, an analysis corresponding to the CPB (Constant Percentage Bandwidth) filtering in acoustics should be performed. The registered signal is filtered through 1/3 octave filters. An octave is a range of frequencies whose upper limit is twice the value of its lower limit; a 1/3 octave is one of three parts of the octave, each of which fulfills the condition that the ratio of the upper and lower limits is constant. For each 1/3 octave an amplitude is determined that, together with the middle frequency of the range, yields the coordinates of the point on the SWD diagram. The analysis is performed by placing the above points on a coordinates system, in which the horizontal axis is the axis of frequencies and the vertical one is the axis of acceleration or displacement amplitudes, and determining which zone the points belong to. In the abovementioned coordinates system, four division lines A,B,C,D were determined, dividing the zones of dynamic influence (zone I, II, III, IV, V). „The following criteria of dividing the zone of harmfulness were assumed:

- zone I – vibration imperceptible to the building,
- zone II – vibration perceptible to the building but not harmful to the construction; an accelerated wear of the building, first cracks in the […] plaster,
- zone III – vibration harmful for the building, causing local cracks and fissures […],
- zone IV – vibration highly harmful for the building […],
- zone V – vibration causes construction failure through the collapse of walls and ceilings”.

Although it is not explicitly stated in the standard, in our opinion, the level of vibration in historical structures should not exceed the values determined by line A.

The greatest disadvantage of the Polish standard PN-85/B-02170 is that it cannot be applied to large-scale structures (churches, chapels *etc.*) and it does not introduce special vibration limits that should not be exceeded in historical structures. [Fragments of standard translated by the authors].

2.2. German Standard DIN 4150-3

In dynamic analyses of historical structures and monuments, the German norm DIN 4150-3 – *Effect of vibration on structures* is much more useful than its Polish counterpart. The norm unequivocally refers to historical structures (“listed buildings under preservation order”), (Table 1), for which it introduces separate maximum permissible levels of vibration (ones much lower than for other types of structures). Moreover, in contrast to industrial structures, even minor damage to historical structures (together with one other type of structures) is considered to reduce their serviceability. Such minor damage includes the appearance of cracks in the plaster, the enlargement of already existing cracks, and the detachment of partitions from loadbearing walls and floors.

There are no limitations to the structure size in the German standard, so it may be applied to large structures such as churches, chapels etc. The standard introduces two categories of vibration: short-term and long-term. Short-term vibration is “[v]ibration which does not occur often enough to cause structural fatigue and which does not produce resonance in the structure being evaluated,” while “long-term” refers to all other types of vibration.

In evaluating the effects of short-term vibration on the structure as a whole, the procedure [2] is:

- “Evaluations as in this standard are based on the maximum absolute value of the velocity signals, $|v|_{i,\max}$, for the three components (where $i = x, y$ or z) of the unweighted velocity signals $v_i(t)$, measured on the building foundation (this parameter is referred to below as *vi* for short)”.
- “The vibration measured in the plane of the highest floor resting on external walls also provides significant information for this evaluation, taking the maximum of the two horizontal components as a basis. Measurements taken at that point […] may be used to determine the horizontal response of the structure to the excitation at the foundation”.

(Table 1) and (Fig. 11) “… give guideline values for *vi* at the foundation and in the plane of the highest floor of various types of building. Experience has shown that if these values are compiled with, damage that reduces the serviceability of the building will not occur. If damage nevertheless occurs, it is to be assumed that other causes are responsible. Exceeding the values at Table 1 does not necessarily lead to damage: should they be significantly exceeded, however, investigations are necessary". To determine which frequency range shown in (Table 1) should be applied, the amplitude of the relevant velocity and the corresponding frequency should be taken under consideration.

Moreover, in cases when "short-term vibration causes floor to vibrate, if v_z is no greater than 20 mm/s when measured at the point of maximum velocity (which is usually at the centre of the floor), a reduction in the serviceability of the floor is not to be expected". "To measure vibration in foundations, the pick-ups for the three directions of measurement shall be placed close together on the ground floor of the building to be investigated, either at the foundation of the outer wall, on the outer wall itself, or in a recess in that wall. In buildings without a basement, the point of measurement shall be no more than 0,5 m above the ground. Measurement points shall preferably be on the side of the structure that faces the source of excitation. The time history of the vertical vibration (*z*-axis) and horizontal vibration (*x* – and *y*-axes, at right angles to each other) shall be recorded, with one of the directions of measurement running parallel to a side wall of the building. For structures with a large ground floor area, simultaneous measurements shall be made at several locations".

In evaluating the effects of long-term vibration on the structure as a whole, (Table 1) "... gives guideline values for the highest value of the two horizontal components measured in the top floor, for different types of building." For historical structures, the value 2,5 mm/s (last row, last column of (Table 1)) is the guideline value – the curve of the guideline value is the purple dashed line in (Fig. 11).

Table 1. (Compiled from Table 1 and Table 3 of the standard DIN 4150-3)

Line	Type of structure	Guideline values for velocity, vi, in mm/s				
		Vibration at the foundation at a frequency of			Vibration at horizontal plane of highest floor at all frequencies	
		1Hz to 10Hz	10Hz to 50Hz	50Hz to 100Hz$^{*)}$	Short-term	Long-term
1	Buildings used for commercial purposes, industrial buildings, and buildings of similar design	20	20 to 40	40 to 50	40	10
2	Dwellings and buildings, of similar design and/or occupancy	5	5 to 15	15 to 20	15	5
3	Structures that, because of their particular sensitivity to vibration, cannot be classified under lines 1 and 2 and are of great intrinsic value (e.g. listed buildings under preservation order)	3	3 to 8	8 to 10	8	2.5
$^{*)}$ At frequencies above 100 Hz, the values given in this column may be used as minimum values.						

The great advantage of the German standard DIN 4150-3 is that it clearly discusses historical structures – curve 3 in (Fig.11). Its disadvantage is the difficulty in interpreting some of the standard's references: in the right column in (Table 1), the standard refers to the vibration of the structure's "highest floor". In the case of churches and other hall (nave) buildings, it is difficult to determine what the term "highest floor" actually means. Similarly, it is somewhat difficult in practice to classify vibration as short – or long-term on the basis of the standard's definition. In such cases, the suitable procedures for short – and long-term vibrations should both be used.

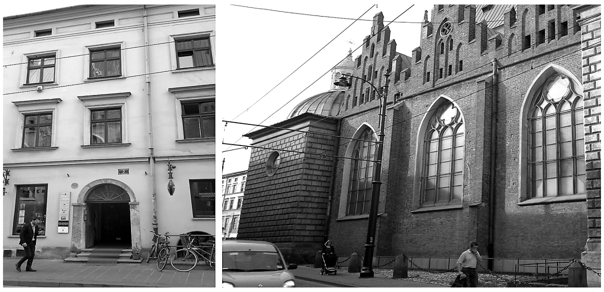

Fig. 8. On the left: No. 3 Dominikańska street. On the right: the Holy Trinity Church from the direction of Dominikańska street. From left to right, the church's chapels are: Lubomirski Family Chapel, St. Thomas' Chapel, the Saviour's Chapel, St. Joseph's Chapel, St. Dominic's Chapel (chapel of the Myszkowski family), and the Chapel of the Rosary

2.3. Example 1 – vibration analysis on Dominikańska street in Kraków

The Holy Trinity Church and the building in Dominikańska street in Kraków are shown in (Fig. 8).

On the side of the church facing the street, along which trams pass, there is a number of chapels. The study of these two buildings is an example of a case where both the Polish [1] and the German [2] standards had to be used: the Polish one for the evaluation of the historical building, and the German – for the evaluation of the church.

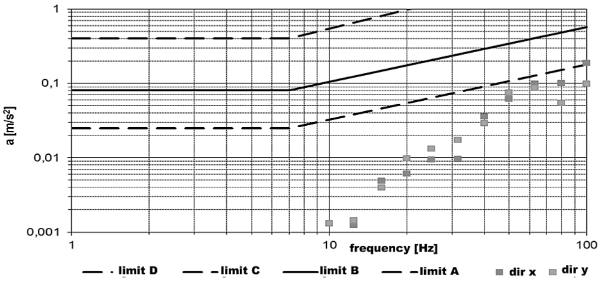

Fig. 9. Evaluation of the harmfulness of ground-transmitted vibration according to the SWD-II scale

In (Fig. 9), the dynamic analysis of vibration of the building on Dominikańska street (Fig. 8, left) due to the passage of a tram, performed according to the Polish standard [1], is presented. It follows from the presented results that the maximum values of acceleration slightly exceed the limit A in one of the 1/3 octaves (the highest one). Limit A is "the lower limit of vibration perceptibility to the building and the lower limit of non-negligible dynamic influence […which causes] vibration perceptible to the building, but not harmful for its structure; only accelerated building wear and the first cracks in […] plaster *etc.* appear." [1]

The dynamic analysis of the vibration of the Holy Trinity Church (Fig. 8, right) due to the passage of a tram was performed according to the German standard. A triaxial measuring system made up of three DeltaTron 8340 accelerometers, fitted to the measuring point on the church wall, is shown in (Fig. 10).

Measurements were taken near the Chapel of the Rosary and the Lubomirski Chapel on the ground floor of the building, i.e. on the level of – 1,4 m below ground. Velocities of vibration were measured in three directions perpendicular to one another, in accordance with [2]. It was found that the amplitudes of these velocities are very small, as shown by the yellow point which, in (Fig. 11), lies well beneath the red curve delineating guideline values for short-term vibration in historical structures. An additional purple dashed line in (Fig. 11) indicates the permissible level of long-term vibration for historical structures (in accordance with (Table 1)). While the passage of one tram is in itself a source of short-term vibration, the traffic on Dominikańska street (which can reach the volume of up to one tram every 0,5 minute in rush hours) may, according to [2], be classified as a source of long-term vibration.

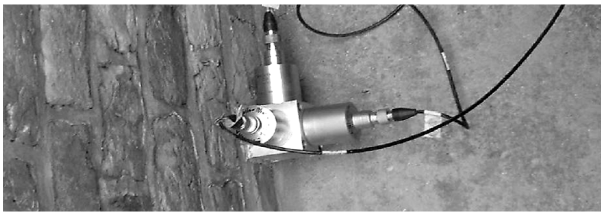

Fig. 10. A triaxial measuring system made up by three DeltaTron 8340 accelerometers

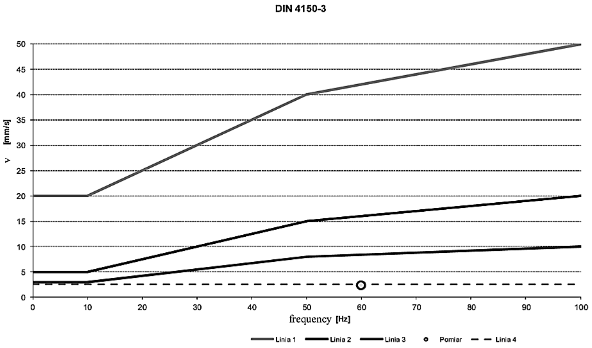

Fig. 11. Vibration influence on the structure of the Holy Trinity Church according to DIN 4150-3

In conclusion, the influence of the vibration due to tram traffic on the structure of the Holy Trinity Church is small. However, in the long term, the appearance of new cracks in the chapel walls is to be expected – as well as the enlargement of already existing cracks, which are even now in evidence as shown in (Fig. 12).

The level of vibration is directly dependent on the velocity of the tram (Fig. 13) that causes it; when the speed of the tram rises from 15 km/h to 40 km/h, the church vibration level doubles.

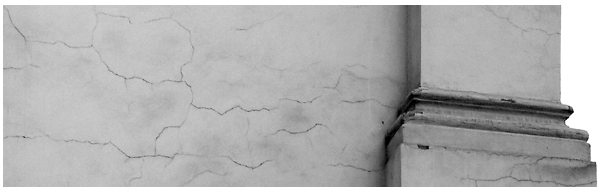

Fig. 12. Cracks in the chapel walls of the Holy Trinity Church

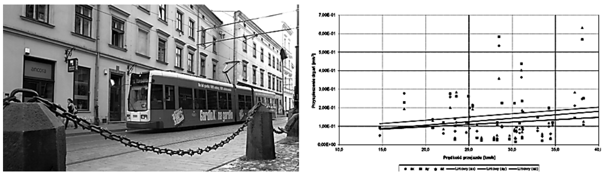

Fig. 13 ."Bombardier NGT6" tram on the Dominikańska street; dependence of vibration level on tram velocity

As a result of the presented study, a recommendation was made to maintain the existing speed limit of 20 km/h for trams passing along the Dominikańska street. As the average recorded speed of trams was 27,8 km/h, and more than 90% of the recorded trams exceeded the speed limit, it was also recommended that the limit be enforced more rigidly in the future.

3. OPERATIONAL MODAL ANALYSIS (OMA)

3.1. The idea of modal analysis

The main idea of modal analysis is to obtain modal parameters H(ω) – modal frequencies (eigenfrequencies), modal forms (eigenforms) and modal damping – on the basis of a measured excitation X(ω) and the structure's response to this excitation Y(ω) (Fig. 14). In civil engineering structures, the greatest difficulty lies in controlling the excitation of vibration while simultaneously measuring the exciting force. For this reason, Experimental Modal Analysis (EMA) is only used in laboratory conditions. In EMA, sufficient force must be applied in order to excite vibration of the studied structure that will be strong enough to be measurable by the sensors. Modal hammers or special vibration exciters are used for this. Both the frequency and the value of the applied force must be known (measured).

In OMA, there is no need to measure the force of excitation, as it is sufficient to measure the system's response to the existing exploitation excitation. However, OMA requires more exact and much longer measurements than EMA. OMA assumes that the excitation – X(ω) – is, theoretically, white noise. Usually, in longer recording time, the real excitation approximately fulfills this assumption (as long as it is not caused by the functioning of machines). Therefore, OMA requires long measurements performed with the use of highly sensitive transducers.

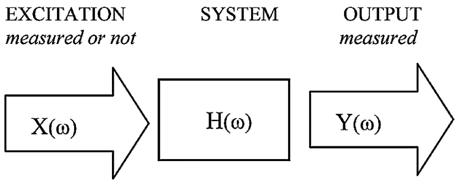

Fig. 14. Measurement-system model for modal analysis

The modal values obtained thanks to OMA may be used to more accurately determine the properties of the model, to add precision to the calculation scheme (which is especially important where it is impossible to take samples for analysis) and to validate the FEM model. OMA may also be used to monitor the structure's technical condition. With any changes in this condition (appearance or enlargement of cracks, material degradation and therefore stiffness change), a change will appear in the modal properties of the structure. Example 2 presents an attempt of using OMA to establish the crack state of the structure.

3.2. Example 2 – Aula Leopoldina in Wrocław

3.2.1. Description of the object and the study

The structure of the ceiling above the Aula Leopoldina is complex, [3, 4]. The main structural elements are wooden deal beams, supported on opposite walls. In the beginning of the twentieth century, the structure was reinforced by introducing

Fig. 15. Main Building of Wrocław University, view from Odra River and the interior of Aula Leopoldina

Fig. 16. View of the Balzer Hall above the Aula Leopoldina. Placement of measuring points in the Balzer Hall is shown in (Fig. 17) and model OMA in (Fig. 18).

additional steel plate girders over every twentieth beam. The planks are supported from below by a c-profile, placed perpendicularly to the beams at about 1/8 of their length from both ends (and thus from the supporting walls). Below this underlying structure, the ceiling of the Aula Leopoldina is covered in valuable baroque paintings (Fig. 15).

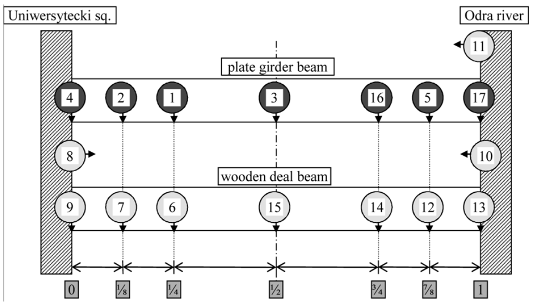

Fig. 17. Diagram of accelerometer placement: THETASHEAR 4507– red colour, DeltaTron 8340 – yellow colour

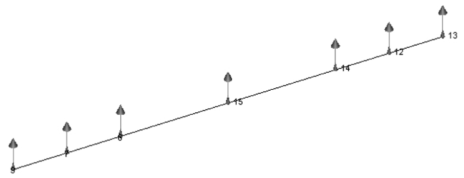

Fig. 18. Measuring points placement on the wooden deal beam – model OMA

The goal of the research (the dynamic analysis was part of a wider research) was to establish if Balzer Hall, the room above the Aula Leopoldina, may be used as a banquet hall. Such a use of the room may be a source of significant dynamic load. The dynamic measurements were performed on one chosen plain girder and the plank immediately below it (Fig. 16).

3.2.2. Modal analysis (OMA)

Using the FDD method (Fig. 19), two eigenfrequencies were identified: 9,7 and 25,8 Hz; using the EFDD, two eigenfrequencies were also identified: 10,14 and 25,68 Hz. The first two eigenforms are shown in (Fig. 20 and Fig. 21) respectively. In the algorithm, it is further possible to identify modal damping, which has been estimated to be, respectively, 14,3% and 1,6%.The relatively large damping for the first mode may be caused by the fact that the movements of separate deals differ in amplitude – their relative movement is therefore big and dry friction appears between them. An imperfection of the anti-symmetry of the second form (which ought to be anti-symmetric) indicates a certain lack of symmetry in the support of the ceiling.

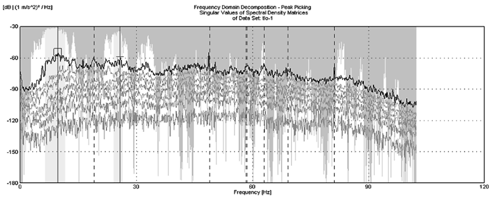

Fig. 19. Singular Values of Spectral Density Matrices

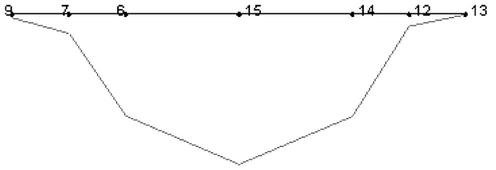

Fig. 20. 1st Eigenshape 9,7 Hz

It was found that the vibration from the “new” ceiling supported on steel plate girders are transferred to the deal beams in their neighbourhood, but are practically not transferred to the deals that are further away. This gives rise to differences in the vibration of the separate deals, which in turn may cause their relative movement. This may result in the appearance of cracks in the plaster ceiling of the Aula Leopoldina, running in a direction parallel to the deal beams. It was therefore recommended that the structure of the floor of the Balzer Hall be separated from the structure of the Aula Leopoldina ceiling.

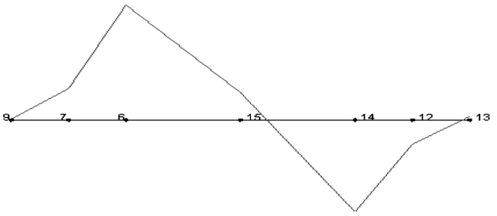

Fig. 21. 2nd Eigenshape 25,8 Hz

3.3. Example 3 – hydropower plant

This example does not deal with a historical building. However, the technology used in this case, which makes it possible to evaluate the crack state of the structure (the depth of the cracks and the possible movement of structural parts separated by cracks), may also be used in historical buildings.

3.3.1. Description of the object and the study

The structure is one of the elements of water accumulation of the water step on the river Wisła. It is made up of three sections with dilatations between them. The structure was built in the 1960s according to a Soviet design. The turbines are also Soviet. Each section is comprised of two hydro complexes. The mass of the generator and turbine with its full equipment is about 883 tons. The turbine shaft is about 1 m in diameter. The underground part of the hydrocomplex consists of the following characteristic parts: inlet spiral, suction pipe and galleries connecting all the hydrocomplexes. These elements are situated below water level and should be waterproof. Unfortunately, the current state of the structure is characterized by the presence of a number of cracks in the concrete of each hydro complex and water leaks through.

3.3.1. Modal analysis

The most important part of the study dealt with suction pipes, where circumference cracks appeared. These cracks could not be diagnosed using any other non-destructive methods due to the presence of water in the pipes. An analysis of eigenforms was proposed as a method of establishing whether the cracks run throughout the thickness of the concrete and whether they work dynamically (the least thickness of the concrete is 2,5 m). (The term „dynamic work of the cracks" describes the possibility of slight relative movement of structure fragments along or across the cracks, as well as the possibility of rotation around each other of the structure fragments separated by the cracks). Discontinuities (breaks and/or jumps) in the eigenform graph, appearing in points on both sides of the crack immediately next to it, indicate that the crack runs throughout the thickness of the concrete and may indicate that the crack works dynamically. In (Fig. 22), the placement of the sensors in the suction pipe Hz6 is shown. Most of the measurements were performed with the use of the seismic accelerometers DeltaTron 8340.

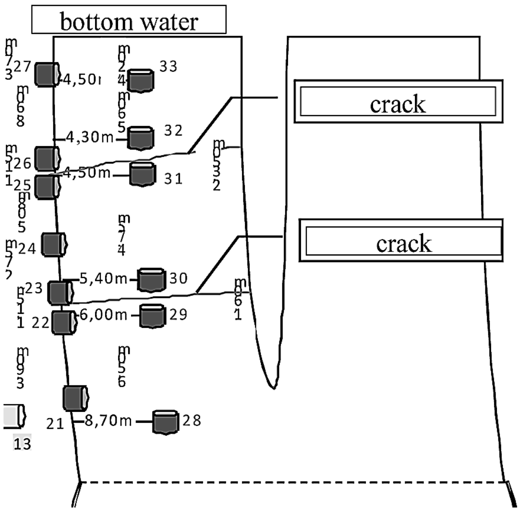

Fig. 22. Measuring points in the suction pipe Hz6 of the hydropower plant

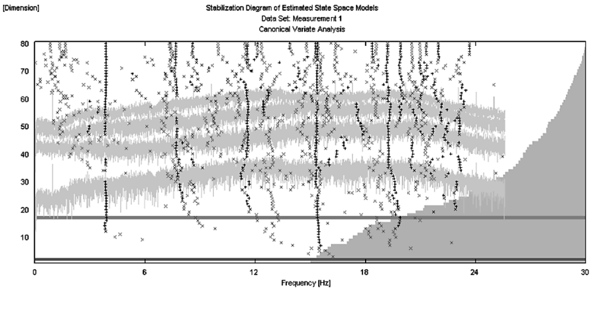

Fig. 23. Stabilization Diagram of SSI (Stochastic Subspace Identification) OMA analysis

Using SSI techniques, the stabilizing diagram for which is shown in (Fig. 23), eigenfrequencies and eigenforms were obtained, shown in (Fig. 24) in green.

In the studied suction pipe Hz6, circumference cracks were found and diagnosed to be running throughout the thickness of the concrete wall of the suction pipe, and to be "working dynamically". These findings were later verified by other, destructive analysis methods.

This example displays the possibility of using OMA techniques to establish the type of damage to a structure. This is a fully non-destructive method that can be used in cases of highly non-homogenous, brittle materials (masonry, stone walls).

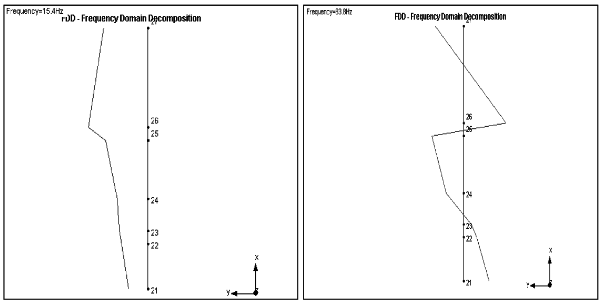

Fig. 4. Eigenforms: first, f1 = 15,4 Hz, and second, f2 = 83,8 Hz

4. CONCLUSIONS

The paper presents contemporary methods and techniques of non-destructive dynamic analyses, which have been chosen with a view to use in historical constructions. The innovation in this approach is the use of two methods of analysis, i.e. theoretical and experimental analyses, to validate and update each other. Emphasis is placed on such analysis methods that ensure a simplified, though not over-simplified, way to achieve a reliable evaluation of the influence of dynamic effects on the behaviour, safety and durability of historical structures and monuments. Simplified methods introduced in Polish and German national standards are described and illustrated with examples of the studied historical structures. The advantages and disadvantages of both approaches are analysed, and conclusions drawn from experience of studies performed according to each are presented.

Alongside the widely used, standard dynamic methods, another approach is also presented: Operational Modal Analysis. OMA is currently the most sophisticated tool for this kind of analysis. This method is used to experimentally study the modal characteristics of a structure during its normal exploitation, without exciting vibration with the use of dedicated devices such as modal hammers or vibration exciters. This is especially advantageous as such "artificial" excitation is difficult to apply to historical structures and may be the source of undue damage to them.

A non-standard, creative method of analyzing the "dynamic work of cracks", developed by the authors with the use of the OMA system, is also presented. Although this approach is illustrated by a study of a non-historical structure (a hydropower plant), it may be used in any structures composed of brittle materials, such as bricks or stonework. It was specifically found that the method is especially useful in establishing whether a crack runs throughout the thickness of the material and whether there is the possibility of relative movement of structure fragments separated by the cracks.

Simple analyses make it possible to observe the studied phenomena quantitatively, without the opportunity to fully evaluate the harmful impact of the vibration on the building.

Simplified analysis procedures introduced by the national standards allow qualitative evaluation, as vibration of a given magnitude may be classified as harmful for the structure. However, these procedures are prone to misunderstandings, as differences in the interpretation of normative expressions occur even among professionals. The use of the non-destructive methods of OMA creates new possibilities of diagnosing damage due to vibration, as it allows a full qualitative evaluation of the analysed structure. In OMA analysis of the structure's vibration, the dynamic influences may be determined on the basis of real dynamic traits of the structure and real forms of vibration. Therefore, the results of the analysis (especially after validation and updating) are fully reliable and do not leave room for differences of interpretation of results. It is for these reasons that OMA provides a wide scope for further development of the diagnostic methods applied to historical constructions.

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Abstract

The research team from the Structural Dynamics Division of Civil Engineering Institute of Wrocław University of Technology performed experimental dynamic studies of a number of historical constructions. The paper presents the most important aspects of contemporary dynamic analyses of historical structures and is a result of the team's decade-long experience with such analyses carried out with the use of the most modern instruments and technologies. The basis of modern dynamic analysis is the use of three elements: *in situ* dynamic measurements, analysis of the obtained data, and calculation on a FEM model. The interrelations among the three are used to validate and update the FEM model. The methods used in dynamic analyses are very complex and difficult. Aside from them, Polish and German national standards offer simplified methods of evaluating the harmfulness of building vibrations due to ground motions. Three types of analysis methods are presented here: simple dynamic analysis, simplified approaches based on national standards and advanced techniques such as Operational Modal Analysis (OMA). The presented studies and measurements are classified as non-destructive, and are therefore best suited to the analysis of historical structures and monuments. OMA merits special attention, as it yields information on modal frequencies, forms and damping. In comparison to Experimental Modal Analysis (EMA), the greatest advantage of the OMA is that no special excitation of structure vibration is required. In large structures, such excitation is difficult to realize and may lead to local damage, which is especially harmful in historical objects. However, OMA requires more exact and much longer measurements than Experimental Modal Analysis (EMA).

Streszczenie

W pracy opisano najbardziej istotne aspekty współczesnych analiz i badań dynamicznych dotyczących specyficznych konstrukcji jakimi są budowle historyczne. Bazowano na doświadczeniach zebranych w tym zakresie przez pracowników Zakładu Dynamiki Budowli Instytutu Inżynierii Lądowej Politechniki Wrocławskiej. Zaprezentowano nowoczesne metody eksperymentalno-teoretycznych badań dynamicznych tego typu obiektów. W pracy przedstawiono proste analizy zarejestrowanych drgań, podejście normowe (na bazie polskich i niemieckich norm) dotyczące oceny drgań przenoszonych na budynki zabytkowe przez grunt, a także zaawansowaną technikę jaką jest Operacyjna Analiza Modalna (OMA). Stosując OMA można określić parametry modalne badanej konstrukcji i na tej podstawie wnioskować o innych jej własnościach i cechach. Główną zaletą OMA jest możliwość wykonania analizy dynamicznej konstrukcji bez specjalnego wymuszania drgań oraz pomiaru tego wymuszenia. W przypadku konstrukcji budowlanych wymuszanie drgań i pomiary sił wzbudzających są na ogół bardzo kłopotliwe w realizacji ze względu na rozmiary i masę budowli. Dodatkowo, stosowanie młotków modalnych bądź wzbudników drgań jest niewskazane w przypadku konstrukcji zabytkowych, ze względu na możliwość uszkodzenia np. cennych tynków lub malowideł ściennych. Ograniczeniem OMA jest konieczność stosowania precyzyjnych i długich pomiarów, a co za tym idzie, konieczność dysponowania odpowiednim sprzętem pomiarowym i oprogramowaniem. Zdaniem autorów, najwłaściwszym sposobem analizy dynamicznej jest harmonijne połączenie trzech elementów: po pierwsze – pomiarów dynamicznych in situ, po drugie – analiz cech dynamicznych modelu eksperymentalnego konstrukcji z wykorzystaniem danych pomiarowych oraz po trzecie – wykonanie niezależnych obliczeń konstrukcji z zastosowaniem jej modelu MES. Wzajemne walidowanie wyników analiz doświadczalnych i teoretycznych oraz otrzymanie jak największej ich zgodności prowadzi ostatecznie do otrzymania wiarygodnych i praktycznie przydatnych wniosków i zaleceń wykonawczych.