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Jerzy WIANECKI, André CHEVALLIER

ACOUSTIC AND AERODYNAMIC STUDY OF NOISE CAUSED BY WIND IN BRIDGE PARAPETS

Summary. Presented study included tests of piece of a bridge parapet carried out in the CEBTP Aerodynamics Laboratory aimed at quantifying noise caused by wind. Next, a research campaign was undertaken in order to attenuate the noise. In the final step of the study, eight new types of parapets were tested, in order to find the one which would provide the most effective suppression of noise, without increasing the cost of manufacture.

AKUSTYCZNE I AERODYNAMICZNE BADANIA HAŁASU WYWOŁANEGO DZIAŁANIEM WIATRU NA BALUSTRADY MOSTOWE

Streszczenie. Przedstawione badania obejmowały testy wykonane w laboratorium aerodynamicznym CEBTP na wycinku balustrady mostowej, w celu kwantyfikacji hałasu wywołanego działaniem wiatru. Następnie podjęto prace badawcze zmierzające do wytłumienia tego hałasu. W ostatnim etapie testom poddano 8 nowych typów balustrad w celu znalezienia balustrady, która zapewniałaby najbardziej efektywne tłumienie hałasu bez zwiększania kosztu jej produkcji.

ETUDE ACOUSTICO-AÉRODYNAMIQUE DU BRUIT PRODUIT PAR LE VENT DANS LES GARDE-CORPS DE PONTS

Résumé. Cette étude effectuée au Laboratoire d'Aerodynamique du CEBTP sur un troncon de garde-corps réel avait pour but la quantification du bruit produit par le vent. Ensuite on a réaalisé des recherches pour trouver des moyens d'attenuation ce bruit. La derniere phase concernait l'examen de huit nouveax types de garde-corps pour choisir celui qui assurerait l'abaissement du bruit le plus important sans augmenter le prix de sa production.

1. INVESTIGATION OF NOISE MADE BY WIND IN BMV TYPE BRIDGE PARAPETS

1.1. Goal of the tests

The problem of noise caused by wind in bridge parapets was submitted to the CEBTP Aerodynamics Laboratory by Somme district Direction Departmental Authority and Planning and the manufacturer "Equipment Routier".

The first phase of the study was aimed at ensuring that the noise of our wind tunnel. This check turned out positive and the second phase, consisting of quantifying the noise by taking acoustic measurements, was conducted.

1.2. Description of the model and its location in the boundary layer wind tunnel (SACLIT)

A 1,5 m long segment of the BMV type parapet, in its standard form, consisting of 10 flat vertical elements, was provided by the manufacturer and placed on the turntable in the first area of SACLIT (see figs. 1,2 and 3).

1.3. Phase I - feasibility study for carrying out the acoustic tests

The segment of the parapet was tested for seven fundamental wind directions: 0°, 15°, 30°, 45°, 60°, 75°, 90° at airflow speeds increasing gradually from 0 to 35 m/s. It has been demonstrated that the strongest audible noises occur for the direction 0°. For this direction, 8 ranges of airflow speed have been obtained. Critical angles, outside of which the noise became inaudible, were investigated around the 0° direction. The results of those test are shown in Table 1.

Table 1

test number	wind speed		audible sound range
	m/s	km/h	
1	13.0	46.7	± 7°
2	16.0	57.6	± 7°
3	18.5	66.8	± 8°
4	21.5	77.5	± 9°
5	24.8	89.3	± 14°
6	27.4	98.7	± 14°
7	30.2	108.7	± 12°
8	34.6	124.7	± 12°

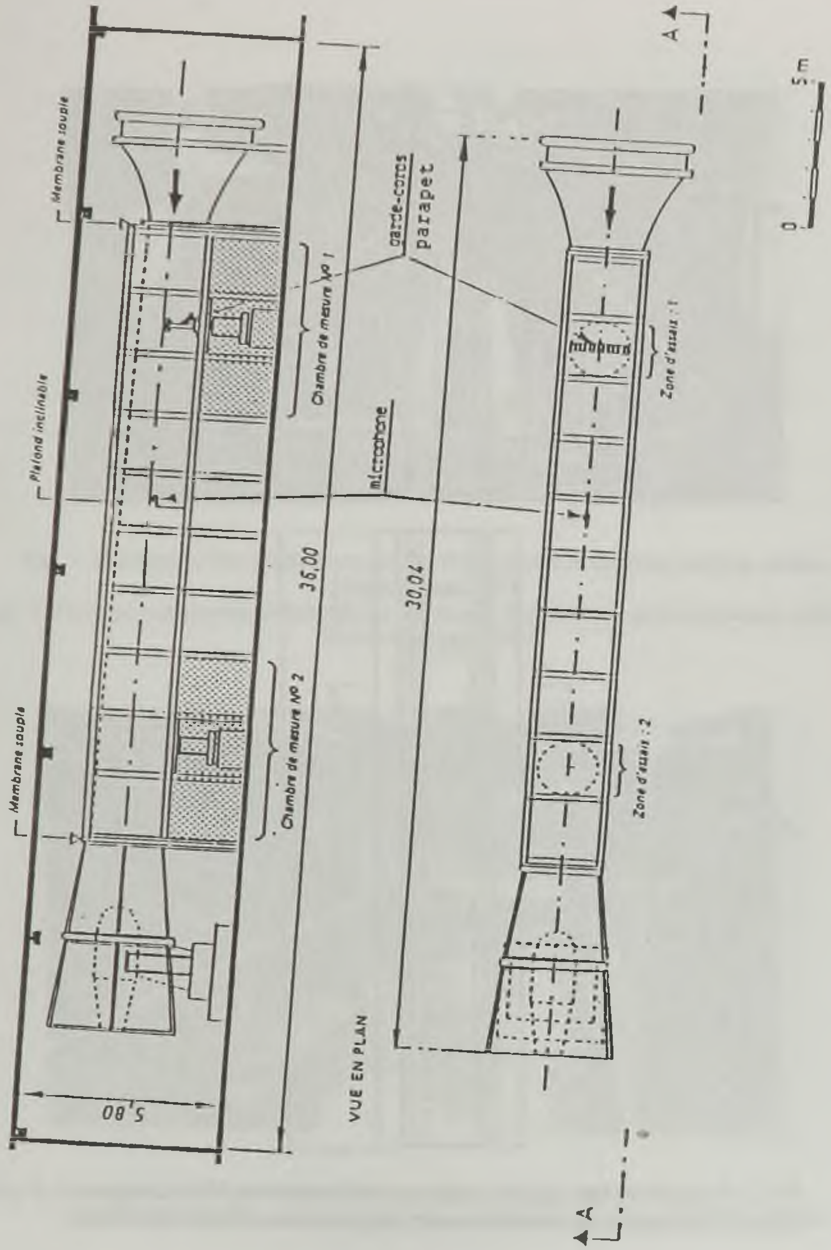

Fig. 1. The boundary layer wind tunnel (SACLIT) at the CEBTP, Saint-Rémy-les-Chevreuse, France
Rys. 1. Tunel aerodynamiczny służący do wyznaczania warstwy granicznej (SACLIT) w CEBTP, Saint-Rémy-les-Chevreuse, Francja

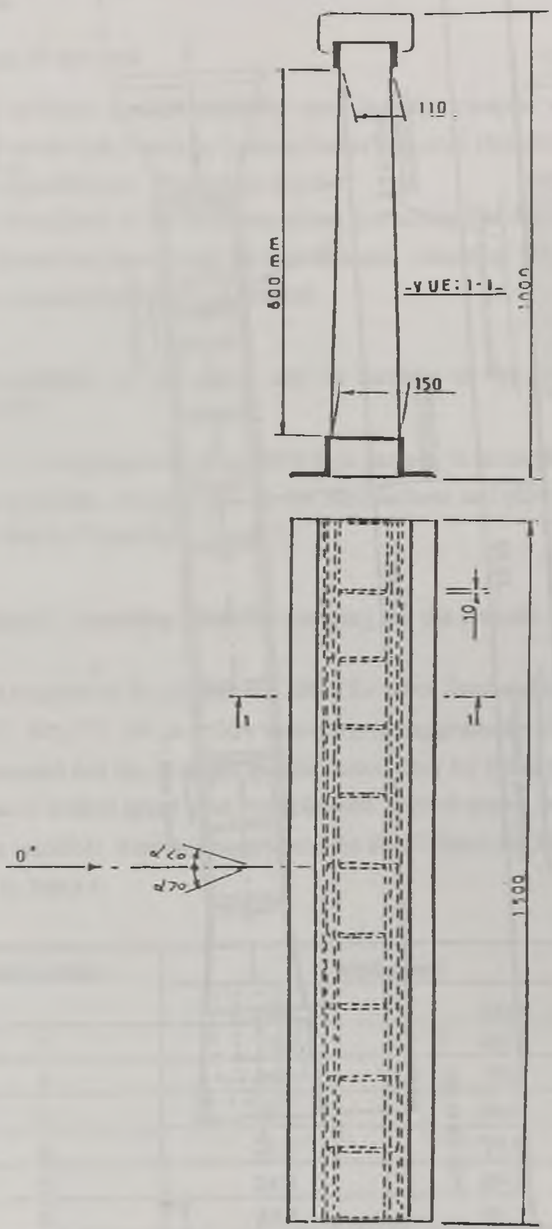

Fig. 2. Segment of the original parapet and its dimensions. Wind direction
Rys. 2. Segment oryginalnej balustrady i jego wymiary. Kierunek wiatru

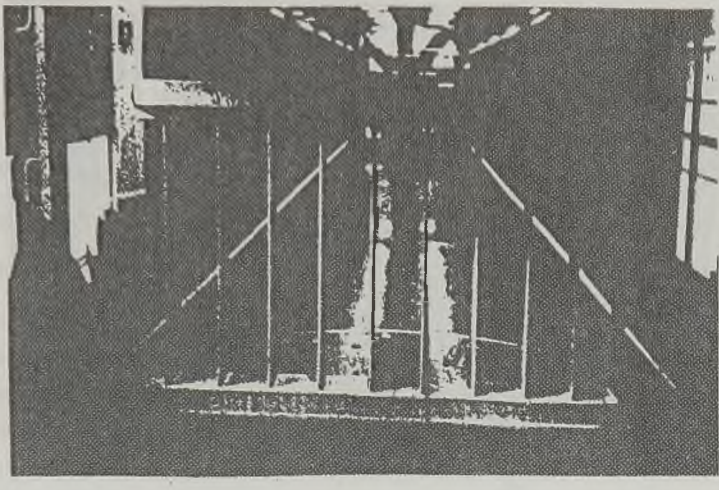

Fig. 3. Segment of the original parapet on the turntable in the first working section. Parapet type BMV
Rys. 3. Segment oryginalnej balustrady na obrotowej podstawie w pierwszej sekcji roboczej. Balustrada typu BMV

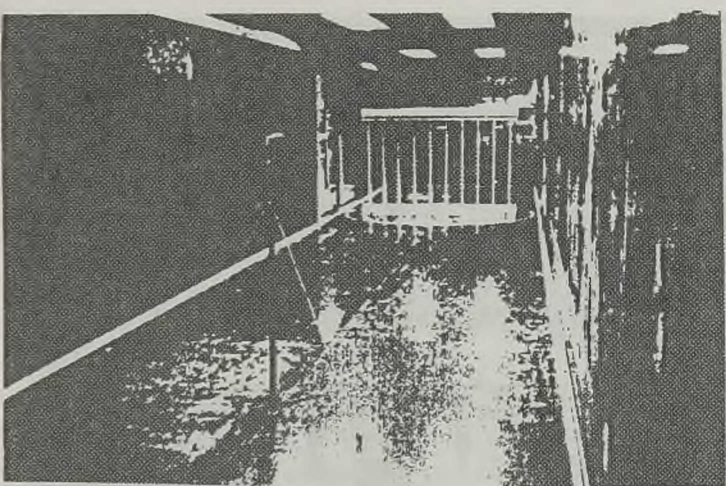

Fig. 4. Microphone located outside of the parapet. Parapet type BMV
Rys. 4. Mikrofon umieszczony na zewnątrz balustrady. Balustrada typu BMV

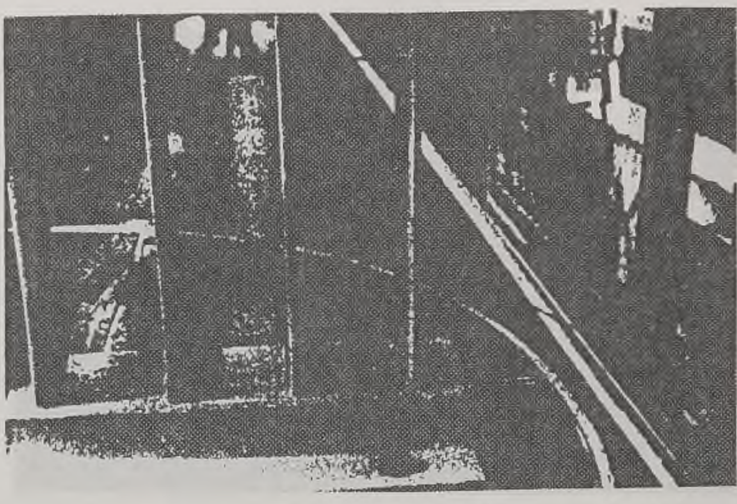

Fig. 5. Accelerometer and impact hammer for measurements of mechanical vibrations. Parapet type BMV

Rys. 5. Przyspieszeniomierz i młotek do pomiaru drgań mechanicznych. Balustrada typu BMV

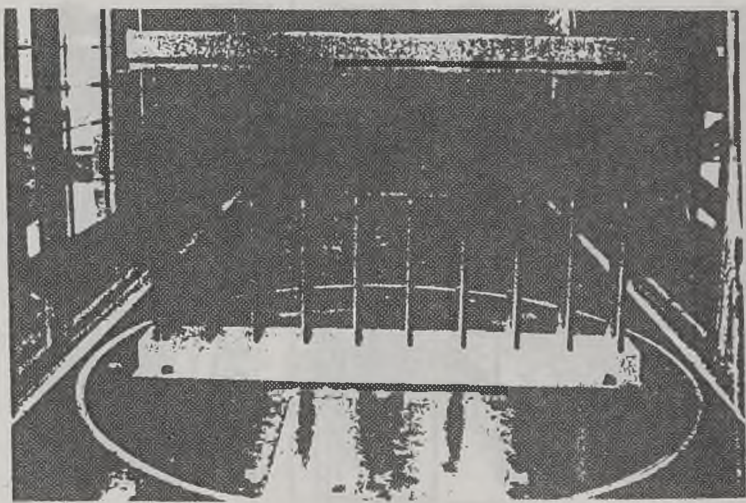

Fig. 6. General view of the parapet with device no. 6. Parapet type BMV

Rys. 6. Widok ogólny balustrady z urządzeniem nr 6. Balustrada typu BMV

The amplified sounds, caused by wind in the bridge parapet at the different wind speeds given in Table 1, were very intense, reaching, at the higher speeds, an extremely unpleasant and even painful, levels.

In the second phase of the tests, the sound levels could be determined quantitatively, using acoustic measurements.

1.4. Phase II- acoustic tests

These tests were submitted to the acoustic Laboratory CEBTP

1.4.1. Methods

The analysis of the problem consists of two distinct parts:

1. Measurement of sound levels for two different configurations.
2. Identification of modal parameters of the parapet, using mechanical excitation.

The first part consisted of measurement of sound levels over a wide range of frequencies (25 Hz - 20 kHz), covering the audible spectrum, inside the airflow of the tunnel with the bridge parapet installed and subsequently without the parapet.

The second part concerned the measurement of dynamic response of a single vertical element excited by an impulse force. The range of frequencies was selected, as a result of analysis of the first part, to be between 0 and 1600 Hz. The goal of the second part was the determination of the fundamental frequency, along with higher order harmonics.

1.4.2. Apparatus

The first part, concerning the measurement of sound levels, was carried out using the following apparatus:

- 1" B&K microphone equipped with a conical element (Figure 2),
- 1/3 octave, 2134 B&K real time analyser.

This measurement system was coupled to a computer system consisting of:

- HP86 computer equipped with and IEEE card and a tape drive,
- HP7225 graphical device.

The appropriate software was designed by CEBTP.

The second part, concerning mechanical vibrations, was carried out using the following apparatus (Figure 5):

- B&K type 4168 accelerometer,
- B&K type 8202 impact hammer, outfitted with a plastic head,
- B&K type 2032 two channel real time analyser.

This apparatus was coupled to a computer system consisting of:

- HP86 - IEEE computer with floppy disk drive,
- HP7225 graphical device.

The appropriate software was designed by CEBTP.

1.4.3. Test procedure

Part 1 - Acoustic tests were conducted for the wind speeds determined in chapter 1.3. The analysis was carried out over a period o 16 s. using linear integration.

Part 2 - The modal parameters were measured using analysis of response of a single vertical element of the bridge parapet, using two different impulse-response pairs:

- accelerometer half way up and half way across the vertical element with the impact on the opposite side,
- accelerometer half way up the element, but on its edge, with the impact on the opposite side.

The coefficient of loss was calculated on the basis of response to the impulse, using manually set frequency windows.

1.4.4. Results

The complete results are presented in the form of tables and diagrams of the acoustic measurements, but only in the form of diagrams for the modal parameters.

Part 1 - acoustic measurements

For every wind speed, a table and diagram of sound levels have been provided separately for the background noise of the tunnel and for the sum of background noise and noise caused by wind in the bridge parapet.

Table 2 shows emergence values (in dB(A)), i.e. the sound values exceeding the background noise of the tunnel, as a function of acoustic frequency and the wind speed.

Table 2

frequency	wind speed in m/s							
Hz	13.0	16.0	18.5	21.5	24.8	27.4	30.2	34.6
315	**17.2**	m	m	m	m	m	m	m
400	7.2	**10.0**	8.3	m	m	m	m	m
500	m	3.4	**26.3**	11.9	11.9	1.5	2.1	m
630	m	m	9.2	**19.0**	**32.5**	**18.4**	16.5	3.2
800	m	m	m	5.8	16.4	8.8	**34.7**	24.6
1000	m	m	m	m	3	m	11.7	**20.3**

m - meaningless

Part 2 - modal parameters

The mechanical response of the vertical element of the parapet, along with corresponding logarithmic damping decrements are shown in Table 3.

Table 3

f in Hz	80	314*	420	1000
δ in %	5	1.3	1	1.3

* this frequency occurs only using a non-symmetrical impulse

1.4.5. Conclusion

Acoustic and mechanical frequencies are presented in Table 4 (combination of Tables 2 and 3).

Table 4

acoustic frequencies in Hz	mechanical frequencies in Hz	comments
-	80	
315	314	in phase
400	420	almost in phase
500	-	sound amplification does not correspond to the mechanical frequency
630	-	
800	-	
1000	1000	in phase

The comparison of acoustic and mechanical frequencies allows us to visualise those frequencies which are in phase, i.e. 315-314, 400-420, 1000-1000 Hz, as well as others, purely acoustic, since the corresponding amplification can not be explained by vibrations of the elements of the parapet.

In those cases, the amplification of sound levels can be explained using the phenomenon of interference of a plane wave, reflected from the vertical elements of the bridge parapet.

In order to attenuate and even completely eliminate those acoustic levels corresponding to the very intense and painful sounds, one should experimentally look for solutions to both the acoustic and mechanical problems.

2. INVESTIGATION OF METHODS FOR ATTENUATING THE SOUNDS CAUSED BY WIND IN THE BMV TYPE BRIDGE PARAPET

2.1. Goal and plan of the tests

The goal of these tests was the search for a method of attenuating the sounds caused by wind in the BMV type bridge parapet, described in the first chapter of this paper.

The description of the model and its position are given in chapter 1.2 and in Figures 1, 2 and 3.

Let us also remember, that in that chapter, the greatest sound amplification was found to occur exclusively for the 0° direction. Thus, the effectiveness of various solutions was studied for that one 0° direction, according to the same phases, I and II, and using the same wind speeds (see Table 1) as previously.

2.2. Tests, results and solutions

The tests concerned seven different devices, attached successively to the vertical elements of the parapet, as described in Table 5. All those devices proved to be more or less effective, namely (see also tab. 2):

- devices no. 1 and 2 eliminate the first two speeds, 13.0 and 16 m/s,
- device no. 7 eliminates the first three speeds, 13.0 , 16.0 and 18.5 m/s,
- device no. 3 eliminates the first four speeds, 13.0, 16.0, 18.5 and 21.5 m/s,
- devices no. 4 and 5 eliminate sound amplification up to the fifth speed, 24.8 m/s,
- finally, device no. 6 turned out to be the most effective and thus, this type of a bridge parapet segment was then subjected to quantitative acoustic tests.

One should point out the fact that although the practical principle of device no. 4 is the same as that of no. 6 (see Figure 6), the latter eliminates acoustic interference between the outermost elements and the glass walls of the tunnel, which do not occur in reality.

As an example of measurements, Figure 7 shows the variations of acoustic sound levels of the tunnel background noise and of the noise including the BMV type bridge parapet fitted with device no. 6. The emergence, eliminated for the speed of 18.5 m/s, is represented by the broken line.

The acoustic levels obtained for 8 wind speeds (see Table 2) do not exceed the background noise of the tunnel.

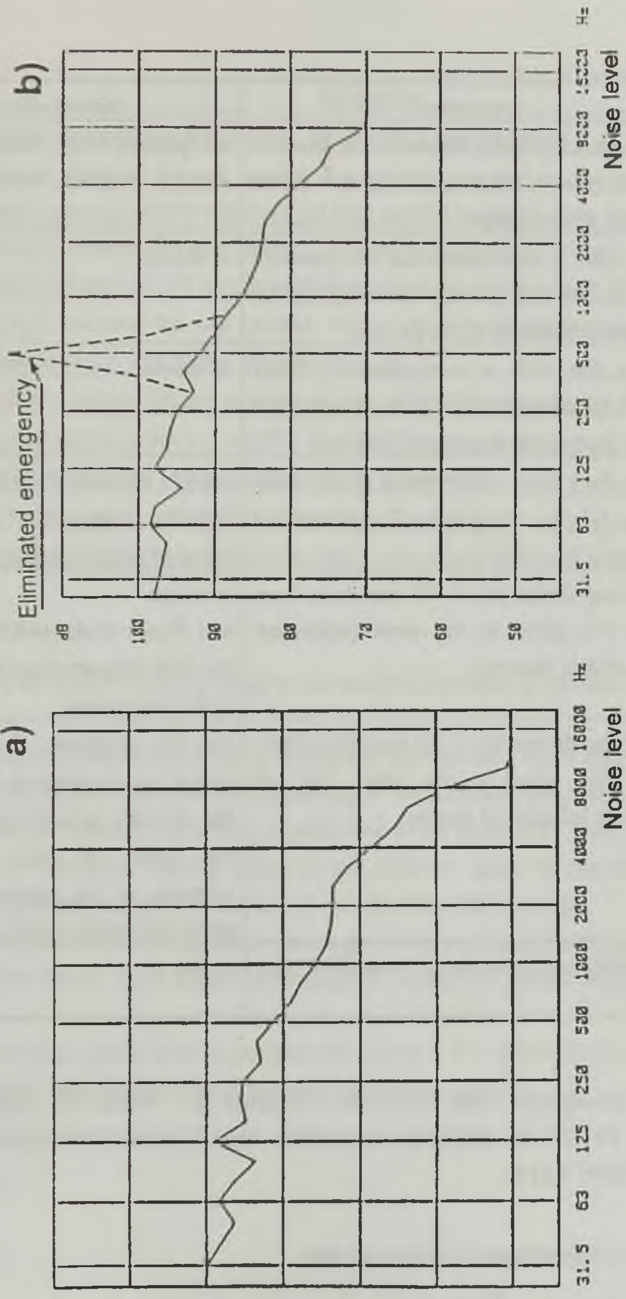

Fig. 7. Noise sectrum in the wind tunnel working section: a) without parapet, b) with the parapet type BMV and device no. 6
Rys. 7. Widmo hałasu w sekcji roboczej tunelu aerodynamicznego: a) bez balustrady, b) z balustradą typu BMV i urządzeniem nr 6

Table 5

device	description	desired effect
1	a bar with a triangular cross-section, glued to one side (always the same) of the ten vertical elements of the parapet	to prevent the detachment of Bernard -Karman vortices
2	a bar with a semi-cylindrical cross-section glued to one side (always the same) of the ten vertical elements of the parapet	as above
3	another bar with a semi-cylindrical cross section, glued symmetrically to the previous one on each of the ten vertical elements	as above
4	10 mm thick foam rubber glued to the entire surface (always the same) of 9 of vertical elements	create element surfaces with different physical properties, between which air flow occurs
5	completing device no. 4, 10 mm thick foam rubber was glued to the tenth (outermost right) vertical element	as above this device concerned the wall of the 10th element close to the glass wall of the tunnel
6	completing device no. 5, 10 mm thick foam rubber was glued to the other side off outermost left vertical element	the two additions, 5 and 6, to device no. 4 aimed at eliminating the acoustic interference between the walls of the outermost elements of the parapet and the glass walls of the tunnel
7	as in device no. 6, but using 3 mm thick hard rubber	as above

3. TESTS OF DAMPING THE SOUNDS CAUSED BY WIND IN EIGHT NEW, DIFFERENT TYPES OF BRIDGE PARAPETS AND THEIR COMPARISON WITH THE BASIC BMV TYPE.

3.1. Description of the different bridge parapets

The description is given in Table 6.

Table 6

parapet	description
BMV	vertical elements flat and parallel, 10 mm thick (see Figure 2)
1	vertical elements flat and parallel, 8 mm thick, coupled by two 60/12 flat iron bars at a height of 375 mm from the base and held together by ϕ 14 threaded bars
2	vertical elements flat and parallel, 10 mm thick coupled by two 60/12 flat iron bars at a height of 375 mm from the base and held together by ϕ 14 threaded bars
3	vertical elements flat and parallel, 10 mm thick with flat iron bars welded at a height of 420 mm above the base
4	vertical elements flat and parallel, 10 mm thick with three rows of ϕ 22 openings
5	vertical elements flat and parallel, 10 mm thick with seven rows of ϕ 12 openings
6	flat elements tilted at $\pm$ 5° to the vertical, 10 mm thick
7	curved elements, with uniform curvature, 10 mm thick
8	curved elements, with variable curvature but uniform height of arch, 10 mm thick

3.2. Tests and Results

The tests were carried out according to the method described in the first chapter of this paper.

The comparison of the different types of parapets with the basic BMV type is presented in Table 7. The comparison was conducted according to the following principles:

- the fundamental values of the critical speeds relate to the basic BMV type; this means that different critical velocities, corresponding to the different types of parapets, had to be identified by approximating them to the critical speeds of the BMV parapet,
- the same approximation, for the same reasons as above, applies to the frequencies,
- if, for a given speed, there occur two emergence values, the greater value was taken as relevant.

Comparison of the meaningful emergence values ($315 < f < 4000$ Hz), for different types of bridge parapets, with the basic BMV parapet is shown in Table 7.

Table 7

			type of bridge parapet															
BMV			1		2		3		4		5		6		7		8	
v	v	em	em	diff	em	diff	em	diff	em	diff	em	diff	em	diff	em	diff	em	diff
m/s	km/h	in dB(A)																
13.0	46.7	17.2	19.7	+3	5.7	-12					-	-						
16.0	57.6	10.0	10.2				13.0	+3	16.6	+7	-	-			5.1	-5		
18.5	66.8	26.3	16.1	-10	23.5	-3	23.2	-3	7.9	-18	-	-	11.3	-15	16.9	-9		
21.5	77.5	19.0	12.0	-7	24.2	+5	21.8	+3	7.9	-11	-	-	18.0	-1	10.7	-8		
24.8	89.3	32.5	25.1	-7	9.8	-23	24.2	-8	8.5	-24	-	-	15.0	-18	14.7	-18		
27.4	98.7	18.4			16.9	-2	14.2	-4	11.6	-6	-	-	18.7	0	8.5	10		
30.2	10.7	34.7							12.8	-22	-	-			9.9	-25		
34.6	124.7	24.6	13.7	-11	25.2	+1	13.2	-11	14.7	-10	-	-	17.6	-7	15.6	-9	5.4	-19.2

em - emergence
diff - difference
(-) - decrease
(+) - increase

NB: The data relating to the parapet no. 5 is not shown in this Table, since its behaviour is very specific and differs from all the others. The parapets BMV, 1, 2, 3, 4, 6, 7 and 8 cause a sound amplification only for directions I = 0° ± 7°, while the parapet no. 5 causes it to occur for directions 0°, 30° and 45° within a range from 20° to 60°.

3.3. Conclusion

The comparisons of parapets no. 1 and 2 to the BMV are characterized by a certain discrepancy, which results from using mechanical connections, the tightness of which can significantly influence the emergence value. Moreover, considering their unappealing appearance, the parapets 1 and 2 should probably be excluded from consideration.

Comparison of parapet no. 3 to the BMV shows a shift of the first critical speed from 13.0 to 18 m/s, while for speeds between 16.0 and 21.5 m/s the results are practically identical (± 3 dB(A)) and finally for higher speeds, there is an improvement, resulting in decreasing the emergence by 11 dB(A) for v = 34.8 m/s.

The behaviour of parapet no. 4 is significantly improved over that of BMV. The emergence values for all speeds are of the order of 10 dB(A), with the exception of v = 16 m/s (16.6 dB(A)) and v = 34.6 m/s (14.7 dB(A)). Still remaining to be solved is, of course, the problem of production costs and resistance to possible vehicle impact.

The parapet no. 5 should categorically be discarded, since it causes a strong sound amplification under the influence of wind, for all of its directions. Thus, its acoustic behaviour is completely different from all the others and very specific in comparison to parapet no. 5, whose behaviour was so significantly improved over the BMV.

The parapet no. 6 demonstrates a shift of the first critical speed from 13 to 16 m/s and consequently and improvement of sound levels (of the order of 10 dB(A)) for all speeds and particularly for 24.8 m/s and 30.2 m/s for which the improvement is -18 and -25 dB(A) respectively. Thus, this type of parapet is quite good acoustically.

Finally, the comparison of the parapet no. 8 with the BMV shows a spectacular shift of the critical velocity from 13 to 34.6 m/s with a decrease of amplification by 19.2 dB(A). Thus, this type of parapet is acoustically the best.

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Recenzent: Prof. dr hab. inż. Stanisław Mierzwiński

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Abstract

The problem of noise caused by wind in bridge parapets was submitted to the CEBTP Aerodynamics Laboratory by Somme district "Direction Departementale de l'Equipment" (departmental authority and planning) and the manufacturer "Equipment Routier". The problem concerned a viaduct on highway 40 and a viaduct forming part of the Somme west ring road in Abbeville.

The first phase of the study focused on the problem of feasibility. It was essential to make sure that the noise from the parapet at a scale of 1:1, exposed to wind, can be distinguished from the background noise of our wind tunnel. This check was found to be positive and the second phase, consisting of quantifying the noise by taking acoustic measurements, was implemented. A 1,5 m long test piece consisting of a normal BMV parapet comprising of 10 vertical elements, was provided by the "equipment Routier" company. It was mounted by the routine installation method and fixed on the turntable in the first test area of the turbulent boundary layer wind tunnel.

The test demonstrated that the amplified sound, emitted by the parapet subjected to different wind speed levels, was very intense. For very high wind speeds, it reached extremely unpleasant, even unbearable, sound levels (emergence of 35 dBA with respect to the background noise).

A research campaign was undertaken in order to attenuate or even suppress these very high sound levels of the BMV type parapet. The unit was fitted with seven different devices, in turn and the final tentative ensured total suppression of noise.

Next, as a final step of the study, eight new types of parapets provided by "Equipment Routier" were tested, in order to find the one which would provide the most effective suppression of noise, without increasing the cost of manufacture. An analysis of these tests contributed to identifying the type of parapet ensuring the best performance.