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ANALYSIS OF DYNAMIC TRAM-TRACK INTERACTIONS BASED ON PARASEISMIC VIBRATION

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In the recent years the directions of development of urban transport in European cities indicate development of tram systems. The consequence of growing trams participation in city traffic is a significant impact on the vibroacoustic climate of urbanized areas. The undesirable effects are the result of a dynamic interaction in tram-track system. This state causes needs to take measures for the proper functioning of trams, ensuring trouble-free and comfortable ride for passengers from the noise and vibration point of view. Most of all these activities should be associated with proper cooperation of trams and tracks, not only to ensure their proper technical condition, as confirmed by recent studies.

The article presents problem of optimization transport process from the point of view the vibroacoustic effects, which are additionally complicated by different types of vehicles and track construction in one tram network. The presented studies contain experimental results of this problem under normal trams operation on the infrastructure in Poznan (PL). The issues relate to the comparative analysis paraseismic vibration as the effect of dynamic tram-track impact. The phenomenon was observed during pass-by tests of one selected tram type on three track sections with described dynamic response.

Keywords: tram, track, dynamic impact, paraseismic vibrations, dynamic structure of tracks

1. Introduction

Currently observed development of urban transport in Europe is oriented to increase the part of trams in urban traffic. This is undoubtedly due to the many advantages of this means of transport, in which the most important is the ability to ensure high mobility of inhabitants, while reducing traffic congestion and a lack of direct emission of harmful substances into the environment [11].This assumption is also the basis of EU transport policy, which supports the revitalization of urban rail transport systems through a number of grants for local governments [2]. All of this contributes to the development of the tram networks in Europe. Both in terms of building and modernizing infrastructure and rolling stock. The consequence of this is the increasing part of trams in urban traffic, which affects the vibroacoustic climate of heavily urbanized areas. Undesirable vibroacoustic phenomena are the result of a dynamic interaction between a rail vehicle and a track at the point of contact in which the rail and wheels generating vibrations and noise [6, 7, 12]. Public transport, that includes trams is the main source of those vibrations in cities. This vibrations are a physical consequence in the macro scale of all the phenomena related to transmission dynamic load, generated by tram traffic on the ground. The values of impact loads, and the level, and characteristics of arising as a consequence of this vibrations, depending primarily on the quality of cooperation between the track and the vehicle, for they form a system of mutual feedback. The main factors affecting this quality are: the type and technical condition of the vehicle and the track, irregularities on the rolling surfaces of wheels, and rails, and driving parameters.

The disturbing fact is that the applicable Polish standards and goverments' regulations regarding the procedures of track maintenance [9, 13] are based only on the periodic visual inspection and geometric measurements of tracks to determine their technical condition and the speed limits. However, without taking into account both parts of tram – track system (systems approach), these measures are not effective form of control of its cooperation quality, especially in the terms of dynamic interactions and their secondary effects, what is confirmed by recent studies [1, 3, 4, 5]. A similar situation applies to the formulate of a specification for new vehicles by the municipal operators of rolling stock. They often contain a notation, saying that trams must be adapted to the existing infrastructure. In practice, such vehicle customization applies only to the width of the track, its minimum radiuses and gauge, excluding consideration of dynamic interactions. Moreover, optimizations of transport process from this point of view is complicated by many different types of vehicles and track constructions, which exists in one tram network. This situation requires taking comprehensive actions for the proper functioning of the tram system. These should ensures the regularity of the passenger service in failure-free and comfortable way for passengers and inhabitants from the point of view of the effects of noise and vibrations. It allows to minimalize the impact on the environment, which positively affects the quality of life [10] and the urban development.

The main aim of this research is a comparative analysis of the paraseismic vibrations generated by chosen type of trams under normal operating conditions, including selected types of tracks. The studies are designed to determine the nature of interactions in selected tram – track systems, especially in the terms of repeatability the phenomena and determination of the influence of the dynamic structure of tracks on the impacts observed during tram traffic.

2. Research methodology

2.1 Procedure of experimental measurements for two-parts research

The study was divided in two parts and have been made as a passive experiment based on in-situ observations on the tram infrastructure in Poznan (PL). The first part, which was the pass-by test, concerned the analysis of the dynamic interactions during passing trams in the normal operation. The second stage of the study concerned the analysis of structural dynamics of tracks based on the inertance functions obtained from the impact test. In both parts, the track's response was measured as accelerations of paraseismic vibrations on the surface of ground level in vertical direction. Fig. 1 shows schematically a study procedure and measurement points.

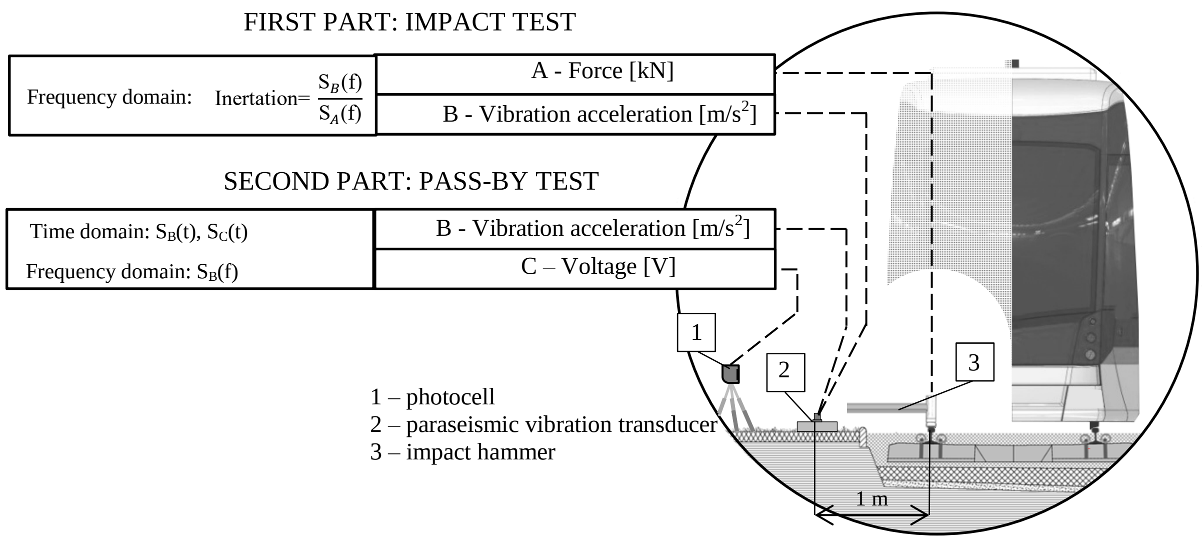

Fig. 1. The procedure for conducting a two-part research

Measuring point for registered paraseismic vibrations was located in 1 meter proximity to the external rail, in cross section of the track. In this section photocell was located on both side of track, its signal were used as a marker for the front part of the tram and the end. It allowed to conducted time selection of vibration signals for further analysis. Moreover, photocell signal was also used to calculate the speed of trams. During recording signals on the second step fill level of tram was being noted, mapped in scale from 0 to 10 (0 - empty tram, 10 - full tram). Measurements for both parts of study carried out in the same measuring points at each track. Piezoelectric transducer Brüel & Kjær Type 8344 was used for registering of vibration signals and complied to the technical requirements. Acquisition and archiving measurement's data was carried out using a multi-channel data acquisition system Brüel & Kjær Type 3050-A-060. The signals were recorded up to the band of 25.6 kHz with sampling frequency of 65 536 Hz. Higher sampling frequency than the requirements from Nyquist–Shannon sampling theorem stemmed from the expected pulse signal extortion in the first stage of the study, similar to the Dirac delta function. The signals were recorded synchronously at all points and measuring channels. Before measurements the calibration process of each measuring equipment was carried out. Constant acoustic and weather (without precipitation) conditions prevailed during the measurements in two parts of study.

2.2 The objects and location of the research

The selection of tracks was used for study based on the criterion of disruption reduction. Selected sections of tracks are ballasted and separated from the road traffic, while being in the highest technical condition, according to the classification of infrastructure owner (8). Selected types of track shown in Figure 2.

Fig. 2. Examined tracks

The studies were conducted on two structurally similar sections of tracks at Warsaw street (track A) and at Starolecka street (track B). Tracks are composed of the rail type 49E1, prestressed concrete sleepers with fixing system type SB-3. The main difference between tracks is the ballasting level. On track A was to the level of the rail head, and on the track B to the sleepers' surface. Moreover, the time of operation since the last modernization for the track A and B was similar and amounted to respectively 13 years and 12 years. The third track was structurally different and was located on Poznan Fast Tram route (track C). The track is composed of the rail type 180S with mouting system type K on wooden sleepers. Besides, it is characterize by the longest operating time for 19 years, since the last modernization. In order to standardize sources of dynamic loads in first stage of studies, were selected one type of tram - Solaris Tramino S105p (Fig. 3).

Producer:	Solaris Bus & Coach (Poland)
Model:	Tramino S105p
Total length:	31,69 m
Total width:	2,4 m
Total height:	3,64 m
Kerb mass:	42 500 kg
Cars:	5
Axles:	6
Max. speed:	70 km/h
Production:	2011-2012

Fig. 3. Tram type Solaris Tramino S105p

The vehicle's construct is based on two driving bogies under the outer body and cars are rolling bogie under the middle car. It is the newest series-produced tram, operated in fleet of Poznan rolling-stock operator since 2011. This type of tram realizes everyday its transportation route on selected tracks.

3. Results

During the study a total of 75 passage trams were registered - on track A of 18 passage, on track B of 12 passage and on track C - 45 passage. The number of passengers in the vehicles were similar, between 1 and 3. For each of them the recorded signal of vibration acceleration of the passage value of RMS (**R**oot **M**ean **S**quare) was calculated with linear signal averaging. Averaging time was strictly dependent on the speed of tram and ranged from 1.7 sec to 5.3 sec. The results obtained for individual passage as a function of tram speed is shown in Figure 4.

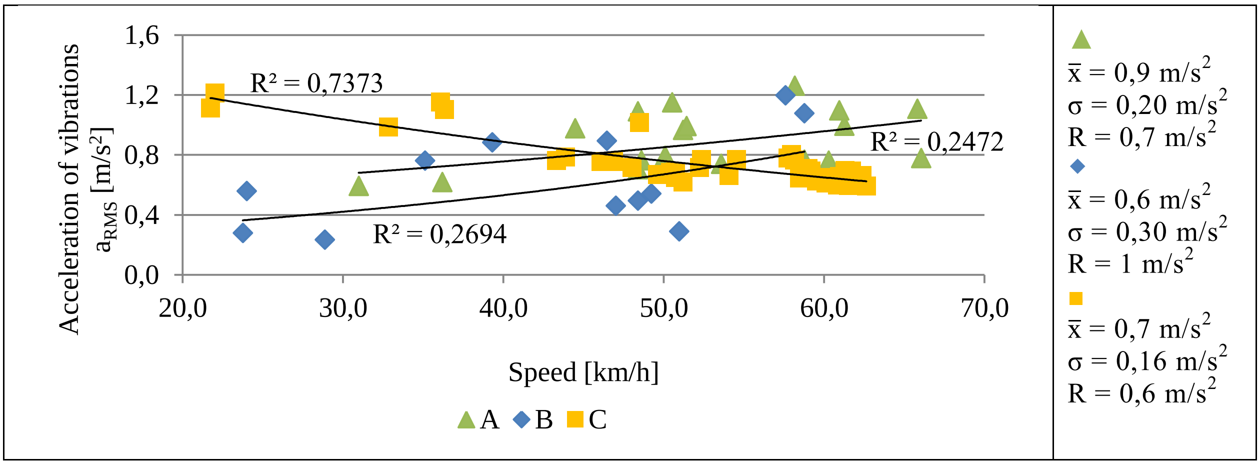

Fig. 4. RMS values of vibration acceleration for trams passing depending on the measured track

As follows from Figure 4, the characteristics of RMS values as a function of tram speed differ from each other depending on the tracks. In the case of tracks A and B, the coefficient of determination was too low for determine the direction of changes based on the exponential model of trend line. Another situation applies track C, where this coefficient was significantly higher and amounted to 0.74. It allowed to determine declining trend in a function of tram speed. It is also possible to classify tracks in terms of the average RMS value of vibration. The highest value of 0.9 m/s^2 was recorded on a track A. For track B this value was lower by 30% and amounted to 0.6 m/s^2 - it was also the lowest value among the examined tracks. Moreover track B is characterized by the largest dispersion of the analyzed phenomena amounted to 1m/s^2 and standard deviation was 0.3 m/s^2. The average root mean square value of vibrations determined for the track C was 0.7 m/s^2 and was 20% lower than the highest value recorded on the track A. Track C and A was characterized by similar values of standard dispersion and deviation, smaller about 30% from values on the track B.

For all analyzed tracks, a significant difference in the generated RMS values of vibration was observed for couples passage with similar speed. There were taken to analysis for two rides with similar speed for each tracks, that generated extreme value of vibrations. In the case of track A, passage at a speed of 48 km/h caused different values of vibrations by 36%. On track B the difference between the values was 49% at speeds 47 km/h and 46,5 km/h. For the track C at a speed of 48 km/h and 48,5 km/h this difference was 30%.

The analysis of qualitative acquired data allowed for the comparison of excited frequency of paraseismic vibrations on examined tracks in both parts of the studies. To accomplish this purpose, the paraseismic vibrations signals were transferred to the frequency domain by FFT (**F**ast **F**ourier **T**ransform) analysis. FFT analysis were also used to designate Freqency Response Function (FRF) to obtain the ineratation functions from the spectra of vibrations accelerance and forces. Reference signal for FRF analysis was force worth more than 1.5 kN in the range of 1,6-13,3 kN. FFT analysis was performed in the frequency range up to 150 Hz with a spectrum resolution equal to 1 Hz and linear averaging of each signal. The averaged spectrum of paraseismic vibrations generated by a passes tram for each tracks is shown in Fig. 5, 6 and 7.

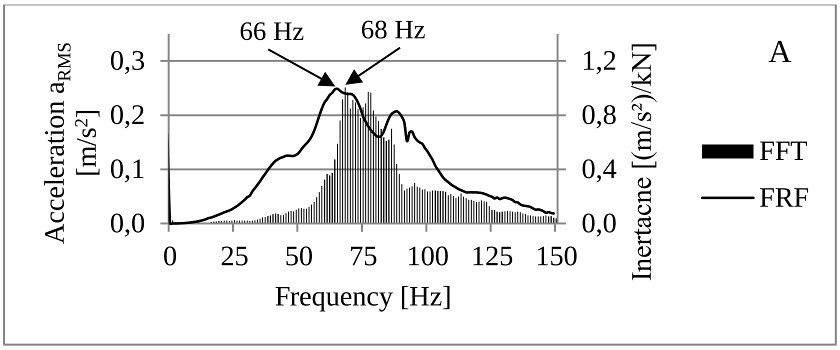

Fig.5. The spectra of vibration acceleration from the passes and the dynamic characteristics of the track A

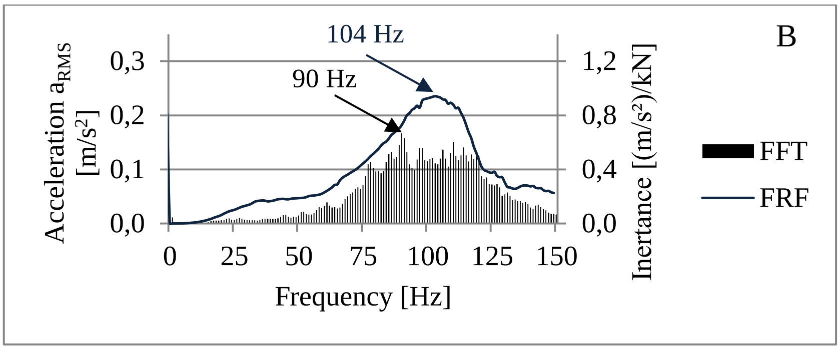

Fig. 6. The spectra of vibration acceleration from the passes and the dynamic characteristics of the track B

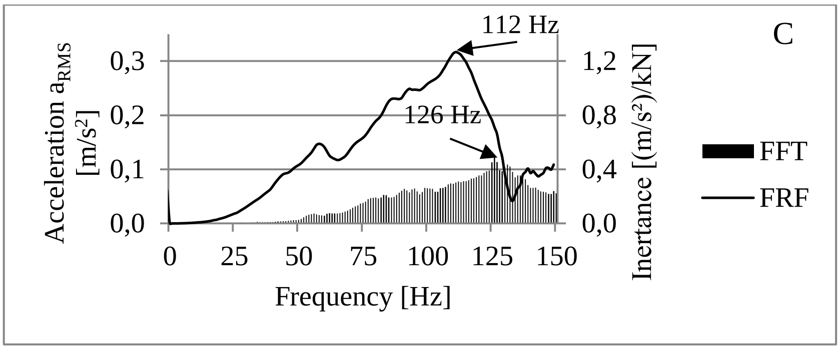

Fig. 7. The spectra of vibration acceleration from the passes and the dynamic characteristics of the track C

The averaged spectra from tram passes differ from each other depending on the tracks. The differences concern mainly the frequency range of excited vibrations and the value and location of the main components in the observed phenomena (Table 1).

Table 1. The list of main differences in the analyzed spectra

	Track A		Track B		Track C	
	Pass-by test [Hz]	Impact test [Hz]	Pass-by test [Hz]	Impact test [Hz]	Pass-by test [Hz]	Impact test [Hz]
Main component of frequency	68	66	90	104	126	112
Main frequency range	65 – 87	58 – 92	85 – 120	87 – 120	111 – 138	86 – 122
Spearman's rank correlation coefficient	0,89		0,96		0,73	

For track A compared to track B track, the main frequency range was located in the lower band from 65 Hz to 87 Hz and was narrower ca. 37%. Furthermore, track A was characterized by higher value of the amplitude ca. 36% for the main component of 0.25 m/s^2, which was located at a frequency of 68 Hz. The main frequency range on track B was widest among examined tracks from 85 Hz to 120 Hz. The main component was located at a frequency of 90 Hz and its value was 0.17 m/s^2. In the case of track C, the main frequency range was slightly wider than for the track A, from 111 Hz to 138 Hz. In this tram-track system the lowest amplitude of the phenomenon was observed amounting to 0.12 m/s^2 for main frequency component, which was lower ca. 64% than the highest amplitude observed at the track A. While main frequency range of vibrations was located at the highest frequencies band of the all tracks.

Spectrum of vibrations accelerations generated by tram on track A and B are significantly reflected in spectra of ineratation characteristics in the entire range of spectra. On track C, there was no such a large dependence between these spectra. This is confirmed by the calculated Spearman's rank correlation coefficients between the vibration acceleration spectra from tram passes and the impact test throughout the frequency range. This coefficient for the tracks A and B was respectively 0,89 and 0,96 and for track C - 0,73. On the track A, the main frequency range for dynamic susceptibility of track include the frequencies from 58 Hz to 92 Hz, and coincides with the frequency range from tram passes at 65%. Moreover, the main component of the dynamic susceptibility and of the vibration accelerations from tram passes were located close to each other respectively at 66 Hz and 68 Hz. On the track B, the main frequency range for dynamic susceptibility of track include the frequencies from 87 Hz to 120 Hz, and coincides with the frequency range from tram passes at 89%. In this case the main components of the spectra were offset from each other by 14 Hz. For inertation characteristic it was located at 104 Hz, and for tram passes at 90 Hz. On track C also observed offset the main components by 14 Hz. For inertation characteristic it was located at 112 Hz, and for tram passes at 126 Hz. The range of the main frequencies of the two spectra coincides each other in 21%.

Spectral analysis were also conducted for selected two representative passes of one (the same) tram with similar speed on each location (Fig. 8).

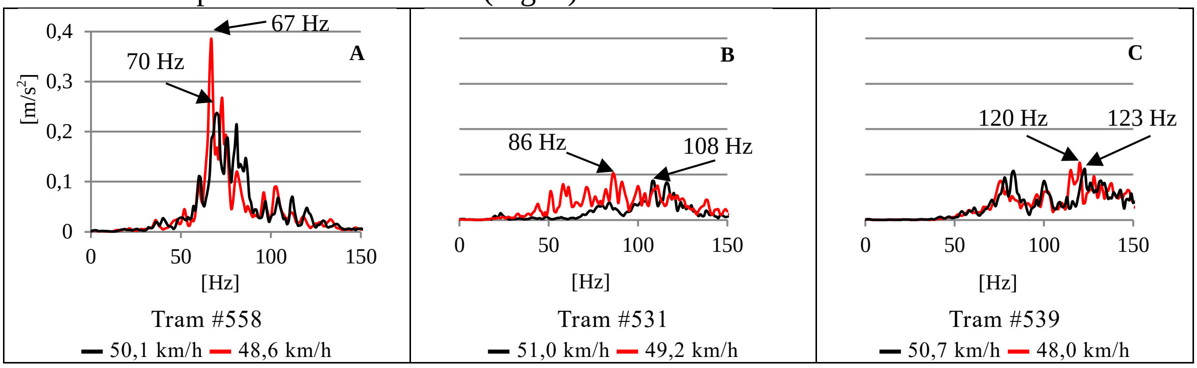

Fig.8. Spectral analysis of two passes of the same tram in similar speed for each measured tracks

Apparent from a detailed analysis of the spectra in Fig. 8, in the case of the tram #558 on track A and C, location of the main components between passes were similar, as in case of the vibration energy with differences of 1,3%. The spectra on these tracks for the indicated vehicles were strongly correlated with a correlation coefficient about 0,9. On the track A difference in main frequency range was 24% between passes of tram #558, but on the track C for passes of tram #539 was significantly smaller about 7%. In the case of tram #531 on track B were significant differences between the indicated parameters. Location of the main components between tram passes was 108 Hz and 86 Hz and differences in main frequency range and vibration energy was higher than 40%. The spectra on these track for the tram #539 weren't strongly correlated and correlation coefficient was about 0,7.

4. Conclusions

The conducted experimental studies allowed to get to know the general nature of interactions in selected tram – tracks systems, which showed the complexity of the discussed issues. Registered paraseismic vibrations accelerations indicate significant quantitative and qualitative differences in the responses of a particular track system and between them, on the extortion from the selected vehicle type. A different character of extortion for the same type of trams was observed, even for the same tram at similar speeds and fill level.

Spectral analysis also shows the differences between tracks in terms of generated vibration from pass-by tests. These differences concern mainly range of excited frequency and the locations as well as values of the main frequency component. Similar conclusions also apply to the inertance characteristic for each tracks, where observed difference in frequency range for dynamic susceptibility. Moreover, the dynamic structure of tracks significantly affects to the characteristics of paraseismic vibration generated by trams. Obtaining spectra of paraseismic vibrations generated by trams are reflected in spectra of ineratation characteristic. This structure is also closely related to the structure of the track, and even the ballasting. Offset the resonance frequency was observed to the lower bands for the track with an increased mass. Besides difference in dynamic structures of tracks, there are other operational factors causes affecting on observed results. The most important of these is the technical condition of individual vehicles and movement parameters which clearly changing boundary conditions of observation.

Results of this study are an important knowledge for local operator of rolling stock and/or infrastructure owner. These results allow to understand the current technical condition of infrastructure from the point of view of applied tracks design and potential environmental benefits - the vibration level paraseismic as the effects of tram-track system operation. This approach can be complementary to the current, ineffective from the point of view of dynamic interactions, geometric measurements of tracks and helping to reduce the cost of comprehensive diagnostic of track system.

Finally, these results could be the basis for the creation of new procedure for assessing the quality of the various types of tram tracks on the basis of determining their cooperation with trams from the point of view of impact on the environment. Moreover, acquired knowledge can be used in making decision at the planning stage of modernization and construction of tracks in the selection of environmentally friendly technologies. It is required to expand research methodology to ultimately minimalize the entropy of the observed the tram - track system, thus reducing factors that randomly affect the measurement results. Only in this way, it is possible to identify the individual processes associated with the generation of noise and vibration signals.

The collected research data will be ultimately used for the diagnosis of the vehicle-track system from the track infrastructure. To achieve this goal a central steps have been taken to build autonomous supporting system T.ROLL-BC (quie**T Roll**ing stock **b**asic **c**oncept) for local operator of rolling stock - MPK Poznan. Moreover, these steps will be used to adapt its functionality to monitor the activity of vibroacoustic activity of trams in the highly urbanized area. This procedure will help to exclude trams which impact will fasten the wear of track and have negative affect on the vibroacoustic climate of the environment.

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Memory

In memory of Bartosz Czechyra - prominent scientist, excellent academic teacher and benevolent friend. Specialist of simulation and experiments in the field of dynamics and vibroacoustics of technical objects and environment. His last scientific work was focused on defining vibroacoustic activity of rail vehicles. Author of over 30 publications, participant of numerous international conferences. Appreciated by collaborators and students for his great enthusiasm and knowledge. Bartosz passed away on September 20, 2016 after a brief, unjust fight against cancer.

"*Tomorrow is today, but tomorrow*" - S. Mrożek

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