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On Certain Problems Concerning Environmental Impact Assessment of Wind Turbines in Scope of Acoustic Effects

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The paper deals with difficulties that are encountered by investors and decision-making authorities in the course of investment processes involving construction of wind power plants. Moreover, attention is focused on absence of standardized procedures that could be used to determine environmental impact of wind turbines, mainly in the scope of acoustic effects appearing in conditions typical for operation of such devices (strong wind), high elevation of related noise sources, and the nature of the sound emission (tonality and amplitude modulation). Lack of such procedures is a source of serious ambiguities developing in assessment of all investment stages — planning and forecasting, construction, and operation. An additional problem arises in the case of power plants located in the vicinity of Natura 2000 area, where construction projects are often obstructed on the grounds of unclear criteria concerning, among other things, the effect of acoustic phenomena on birds, bats, and other animals. It follows from the research presented in this paper that the consistent system of procedures and criteria should be worked out on the grounds of long-term monitoring studies.

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1. Introduction

Construction of a new wind power plant becomes frequently a source of emotions, sometimes evolving into disputes, conflicts, and protests among local communities. Numerous international associations have been established, gathering both fervent enthusiasts supported by the wind turbine manufacturers' lobby and avowed opponents of wind farms backed up by authorities responsible for wildlife conservation. In view of continuously shrinking availability of areas offering favorable conditions both from the windiness and access to electric power network in Poland, such projects start to cross borders of areas on which they would require a more detailed assessment. In order to improve the overall quality of reports providing statutory environmental impact assessments and forecasts predicting such impact, experts from FNEZ (Foundation for Sustainable Energy) in cooperation with GDOŚ (General Directorate for Environmental Protection) have worked out *Guidelines in scope of forecasting environmental impact of wind farms* [1]. However, information contained in the document pertains mainly to administrative and legal requirements applicable to wind power plants, without any detailed reference to technical solutions. The guidelines contain also recommendations concerning "good practices" applicable to drawing up good investment projects and compiling reliable reports on expected impact of such undertakings on natural environment.

Such Provinces as Lubuskie, Zachodniopomorskie, Warmińsko-mazurskie, Podlaskie, and Podkarpackie, which are regions of potentially attractive for investors on one hand, on the other are characterized with the highest share of Natura 2000 areas which represent 19.8% of Poland's land are, including 144 special bird protection areas. Despite unquestionable necessity to develop a system of environmentally clean energy sources in Poland, investors' requests for construction permits are frequently dismissed for reasons relating to negative assessment of the effect of the planned undertakings on the natural environment.

An example of problems arising in connection with construction of wind turbines in the neighborhood of Natura 2000 areas are wind power plants in Górowo Iławeckie and Sępopol. The farms were planned to be constructed on the Natura 2000 special bird protection area "Ostoja Warmińska" (Warmia Reserve). This area is a refuge of white stork sustaining 2% of its total population, and one of the most important refuges for lesser spotted eagle, sustaining 5% of the whole population of the species. Moreover, the area is also a sanctuary for 46 bird species listed in Annex I to the Birds Directive [2], representing mainly the breeding species. Indeed, the report on environmental impact of the planned wind farm project admitted the necessity to determine actual value of individual fragments of the area, make location of farms conditional on the obtained results, and thus avoid any substantial hazard to the birds, but objectors to the undertaking were still able to demonstrate insufficiency of information provided in the investment documentation not allowing to exclude possible negative impact of the planned investments on the environment. Planned location of wind farms were selected regardless of routes used by birds of protected species to access their main preying areas, and assessments of expected impact of the planned investment project on bats have been carried out in an

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inadequate scope and with the use of improper methodologies. It is however unclear whether different positions taken by authors of the report on one hand and the reviewers on the other were the result of negligence on the side of experts compiling the assessment or ambiguous requirements and criteria applicable to assessment of environmental impact of wind turbines.

A draft version of document entitled *Guidelines concerning the impact of wind power plants on bats* [3], content of which was consulted with practitioners and experts dealing with protection of bats in the territory of Poland, presents a harmonized and precise system of research methods in line with recommendations of the Agreement on the Conservation of Populations of European Bats (EUROBATS). However, authors of the proposal note with regret that the negative impact of barriers on migration routes and the scary effect forcing bats to leave their feeding grounds in connection with already existing wind power plants is still unsatisfactorily identified. The related analysis is hindered by the fact that reaction of these mammals in the contact with wind power farms are different in individual species. Population of bats in Poland can be categorized into groups characterized with different degree of exposure to fatal thread in collisions with wind power turbines: species with very high, high, moderate, low, and very low exposure to mortality. The high risk group comprises bat species that fly fast but not very nimbly, prey in the open air, and undertake seasonal migrations. However, there are regions where a very high activity of bats is observed with very low mortality. A thesis has been therefore put forward that mortality among bats is usually positively correlated with power plant's tower height, rotor diameter, and rated turbine power; however, possible correlation between the noise emitted by wind farms with activity variations or just mortality among bats was not discussed in the report. In view of the fact that the poorly recognized impact of wind power plants on bats becomes apparent most distinctly only after putting turbines into operation, any report on potential environmental impact of the investment may be considered insufficient already at the moment of submission.

The negative impact of wind farms on birds and bats is discussed in numerous scientific papers, however both nature and scale of the involved effects, as it has been already mentioned above, are very different and difficult to estimate. Literature of the subject analyses the adverse effect of wind farms on birds in the following four aspects [4, 5]:

- Killing as a result of collision of birds with fast moving rotor blades (collision mortality). On the other hand, bats, despite their echo ranging abilities, die as a result of lungs rupture caused by rapid pressure drop (pulmonary barotrauma). The risk of collision, similarly as in bats, depends strongly on bird species [5]. The high-risk group includes mainly the birds of prey (*Accipitriformes*, predators), and in particular, white-tailed eagle, red kite, common buzzard, and golden eagle, with Eurasian skylark alike representing a high percentage among the victims. High susceptibility to collisions is also characteristic for birds migrating in the night;
- Scaring the birds off both in the stage of construction and later in the course of operation by noise and vibration that can results in driving them to other locations and loosing their previous breeding grounds or feeding areas (displacement due to disturbance);
- The so-called barrier effect — constrained changes of passage routes where a wind farm located on the flight route between the roost site and the preying area forces the birds to take a roundabout way twice a day (or more times in the case of birds feeding their nestlings) for up to 100 days in the year in some cases, which may result in an increased cumulative energy consumption and correspondingly increased mortality among birds;
- Loss of habitat areas and feeding grounds as result of transformation of the land (habitat change and loss).

The examples quoted above represent only a fraction of issues that the investors planning erection of wind farms must stand up to. Moreover, it turned out to be impossible to work out any clear stance with respect to possible harmfulness of wind turbines and in case of its actual existence, develop any explicit assessment criteria. The reasons include, among other things, diversity of wind turbine designs and methods used in working out the statutory environmental impact assessment. An important factor is also the subjective selection of research methods applied when review papers are compiled — results differ significantly depending on who, wind turbine construction supporters or opponents, are authors compiling or employers commissioning making out the environmental assessment report.

No research is currently conducted that would be aimed at determining the effect of sound emitted by wind farms in Natura 2000 area although it is a well-know fact that such noise is the source of occurrence of the barrier effect and scaring the birds off, ultimately resulting in driving them from their habitats.

2. Legal instruments concerning the effect of wind turbines on environment

Because of lack of sufficiently detailed legal regulations concerning assessment of environmental impact of wind turbines in scope of acoustic effects, authors of the assessment reports use methodologies and standards pertaining to industrial noise (generated by manufacturing plants). In view of specific conditions in which the turbines operate, i.e. high wind speeds and location at large altitudes, as well as the specific type of the noise they emit, currently applicable methods used to asses the effect of such noise raise doubts in all stages of the proceedings — modeling, measuring, and applying assessment criteria. Fundamental legal instruments applicable currently to the subject matter discussed here include:

- The Act 'Environment Protection Law' of 27 April 2001 [6], Division V 'Protection Against Noise', as a higher-order document, together with executive acts, especially Regulation [7] of the Ministry of Environment of 4 November 2008 on requirements in scope of carrying out measurements of emissions and measurements of water intake and Regulation of 14 June 2007 on admissible noise levels in the environment [8];
- Act of 3 October 2008 on providing information on the environment and environmental protection, public participation in environmental protection and on environmental impact assessment, regulating the course of issuance of environment usage permits, in this case concerning assessments of impact on Natura 2000 areas necessary to obtain the building permit [9].

From the point of view weather conditions, the method applicable for determination of acoustic power, which is the basic input quantity for further calculations, remains still ambiguous. In this aspect, it is possible to use methods proposed in the European Noise Directive (END) [10], EN ISO 3744 (the engineering method) [11], EN ISO 3746 (the survey method) [12], and ISO 8297 [13] (the engineering method dedicated for small enterprises) or, on the other hand, the method specified in EN 61400-11 [14] and dedicated for measuring noise (sound power) generated by wind turbines. Nevertheless, none of the methods is described as the "recommended" one. In view of the above, even in the initial stage of modeling the noise pattern in vicinity of wind turbines, it is possible to use different methodologies. It is also necessary to note that in many cases, turbines installed in Poland were operated earlier elsewhere, sometimes for many years, and therefore the are likely to represent rather obsolete construction designs.

According to commercial specifications, the acoustic power level for wind turbines quoted by different manufacturers may vary from 98 to 115 dB(A) for units with rated electric power from 0.5 MW to 2 MW and at wind speed of about 15 m/s measured at the nacelle altitude. Typical heights of wind turbine towers are 70 m, 80 m, or 100 m, with blade length reaching up to 50 meters.

It is worth mentioning that the main source of sound emitted by a wind turbine, i.e. the aerodynamic noise generated by rotor blades, is typically modeled as a point omnidirectional source located at a height corresponding to the turbine nacelle altitude. Actually, wind turbines are directional sources with maximum noise levels occurring to leeward of them.

Another stage of determining the noise distribution pattern involves the use of calculation algorithms. In most countries of the world, including Scandinavia with its most dense network of wind turbines, algorithms based on ISO standards 9613-2 [15] and 9613-1 [16] are used. However, ISO 9613-2, although commonly recognized as the most useful for modeling noise propagation in the environment, pertain to sources located up to 30 m above the ground level (a.g.l.). The main noise sources, i.e. the nacelle and rotor blades, are mounted much higher, and additionally end parts of the blades are in permanent motion with linear velocity falling usually in the range 70–100 m/s. The blade tip representing the main source of noise is characterized with varying height above the ground level and thus operates in variable (changing with the height) sound propagation conditions. Another factor raising doubts in connection with application of the standard to modeling noise generated by wind turbines is the ground factor default value of which assumed in the WindPro program is $G = 1$. Such assumption is disputable from the physical point of view as the ground impedance, value of which is essential for determining the damping factor, depends not only on the ground structure but also on the sound wave incident angle that varies with elevation of the source. Further reservations concern the method of taking into account the wind direction and velocity. In the case of classic noise sources, calculations can be carried out for windless conditions, but in the case of turbines, the wind is the natural environment for operation in which they are designed. Algorithms provided by this standard allow to perform only the calculations "with the wind" without its speed and height-dependent gradient profile taken into account.

Wind turbine noise measurements are not just sound power surveys, but also environmental studies that are required (in Poland) to be carried out in accordance with the reference methodology [7], therefore with all its provisions taken into account. Conditions concerning applicability of the method provide for some limiting weather conditions with the maximum wind speed is 5 m/s at height of the measuring microphone (4 meters in a developed area and 1.5 m for an undeveloped area). In the case of measurements aimed at determination of acoustic impact of wind power plants on the environment, noise measurements can be considered reliable only when the monitored turbine reaches its rated operating condition. This occurs for the wind speed above 10–12 m/s at the nacelle altitude (70–100 m) which translates to about 7 m/s at altitude 10 m and a similar speed at 4 m a.g.l. At wind speeds of the order of 3–5 m/s at height of 4 m, wind turbines work well under their rated power and thus are much less noisy. A negative effect of the wind speed on the acoustic pressure measurement results has been taken into account in the standard PN-EN 61400-11 [14]. According to provisions of the norm, measurements are to be taken in at least four points around the power plant. A microphone, protected with two windscreens, is placed on a dedicated circular plate with the diameter of 1 m as a minimum located directly on the ground (0.05 m a.g.l.). At the same time, measured are: the equivalent A-weighted sound level; spectrum in 1/3 octave bands; rotor rotation period; and wind velocity and direction. Adoption of such methodology allows to obtain: the acoustic power level; noise emission as a function of wind speed; directivity; emission levels in 1/3 octave frequency bands in the range 0.8–20 kHz (including infrasound and low-frequency noise), tonality, and pulsation characteristics including amplitude modulation. Application of the method specified in EN 61400-11 [14], though allows to carry out measurements at higher wind speed (above 5 m/s), does not solve the problem of conversion of the value measured on the ground level into the height of 4 m a.g.l. A strong, if not the strongest, controversy is aroused by wind turbine noise assessment carried out taking into account the criteria applicable in the light of Regulation of the Minister of Environment [8] which are based, for the purpose of establishing conditions of the use of environment, on equivalent noise levels L_{AeqD} and L_{AeqN}, [17], while the criteria determined in the long-term environment noise protection policy refer to levels L_{DEN} and L_N [10]. There are therefore no grounds on which authors of environmental impact assessments would be obliged to take into account some characteristic features of noise generated by wind turbines, namely the amplitude modulation and tonality, as well as the infrasonic noise issue frequently raised by the opponents protesting against erecting wind farms in sensitive regions.

Lack of unambiguous and detailed legal instruments within the scope of wind turbine noise assessment results, just like in the case of measurement methodologies, in situation where criteria used to assess arduousness of noise generated by turbines are the same as those applicable to other noise sources (i.e. to the industrial noise) [8], which stirs up significant (and understandable) controversy.

While the methodologies used to assess the impact of noise generated by wind turbines on humans are already relatively consolidated, though still lacking sufficient establishment in legal instruments[†], the impact of wind turbine noise on the animal kingdom lacks practically any specifically oriented research back-up. Opinions concerning the issue of sensitivity of the animal world to noise range from views equaling it with reactions demonstrated by humans to firm claims that the animal kingdom is much more sensitive to alien sound including, of course, the noise coming from wind turbines. None of these stances should be accepted unconditionally, at least because of the fact that animals (and birds) have quite different "hearing characteristics", in any case far from being recognized. Moreover, the phenomenon of the noise itself encompasses not only an "objectively" measured A-weighted sound pressure level, even if corrected for pulsation and tonality, and in the case of wind turbines additionally for amplitude modulation; on the contrary, noise must be considered as a subjective factor, taking into account also such circumstances as e.g. the time of the day and the place where the subjects (people or other animals) are exposed to this type of hazard. In view of quite frequent (and costly) instances where investments planned in the neighborhood of Natura 2000 areas are obstructed because of, among other things, excessive noise generated by them, there is an urgent need to carry out research allowing to make noise assessment criteria applicable to Natura 2000 areas more objective, especially for wind turbines taken into account as a good example. The doubts raised in the above-mentioned opinions have been also confirmed by own studies carried out by the present authors on the wind farm site in Łęki Dukielskie.

[†]In Poland, studies aimed at working out a methodology for wind turbine noise measurements are now in progress.

3. Acoustical studies on Łęki Dukielskie wind farm

The study was carried out on the wind farm site in Łęki Dukielskie (Podkarpackie Province) put into operation in 2009. The facility comprises 5 wind turbines manufactured by REPower with rated electric power of 2 MW, rotor diameter (blade span) of 92 m, and tower height of 100 m each. The electric power units installed in the farm are MM92 models typically used in areas with low or average wind speeds. Annual output of this wind power plant is estimated as 20–24 GWh. The investor was a Portugal company Martifer Renewables, and since 2011 the farm is owned by IKEA group.

In the territory of Gmina of Dukla, the following Natura 2000 areas exist [18]:
1) habitat areas: Ostoja Magurska, Ostoja Jaśliska, Jasiołka, Trzciana, and Łysa Góra;
2) areas subject to the Birds Directive: Beskid Niski. The forest fauna refuges are populated by e.g. brown bear (*Ursus arctos*), wolf (*Canis lupus*) and Eurasian lynx (*Lynx lynx*). Reserves Kornuty and Kościół in Bednarka are habitats of Geoffroy's bat *Myotis emarginatus* and Bechstein's bat *Myotis bechsteini*. Areas subject to provisions of the Birds Directive in the Beskid Niski mountains are the habitat of, among other species, black stork, lesser spotted eagle, golden eagle, com crake, Eurasian pygmy owl, Ural owl, European nightjar, kingfisher, gray-headed woodpecker, white-backed woodpecker, Syrian woodpecker, three-toed woodpecker, red-breasted flycatcher, lesser spotted eagle, Ural owl, and golden eagle. Some species living in the Beskid Niski area are listed in Poland's Red Book as the endangered ones.

The environmental impact assessment for the planned investment has been carried out in 2003 and presented for public consultations in 2004. According to independent opinions on the effect of the investment on birds worked out at that time, no essential hazards to the environment were found. Next, in the year 2010, a meeting of the National Committee for Environmental Impact Assessments was held. As a result of analysis of the documentation concerning environmental impact of undertakings involving construction of another wind farms and planned to be realized in Podkarpackie Voivodship, the Committee raised objections concerning documentation submitted in the framework of the permit granting procedure. Its opinion pointed out the lack of sufficiently exhaustive information concerning the effect of investment on species protected under the Birds Directive and the Habitats Directive, improper scope of ornithological and chiropterological studies, and lack of analyses taking into account various cumulated effects. In the final conclusions, the Committee stated that in view of their location and scale, the planned undertakings might have significantly negative effect on the environment. Requests for positive opinions filed to the Committee and concerning subsequent investment plans in the area were dismissed.

In view of the above, acoustical studies carried out for the wind farm in Łęki Dukielskie, located in the vicinity of Natura 2000 area can constitute an important contribution to discussion on undertakings that have a significant impact on the natural environment. Relevant measurements were carried out by the present authors several times, i.e. in November 2011, and in August and December 2013, in different weather conditions (ambient temperature, atmospheric pressure, humidity, wind speed, the land's vegetal cover).

4. Measurement methodology

The study on the wind farm site in Łęki Dukielskie was carried out according to two different methodologies: (1) the reference methodology [7], i.e. with the microphone placed at the height of 4 m a.g.l. and equipped with a standard windscreen, and (2) according to the methodology recommended in standard [14], i.e. with the microphone placed on the plate but equipped with a single windscreen.

4.1. Example results

Results of measurements of noise generated by wind farms are presented below in the form of acoustic pressure level spectrum not corrected with A or G weighting curves, i.e. L_{LINeq}, in 1/3 octave bands. Such approach allows to identify low-frequency components of the spectrum, including infrasound, for variants involving corrections with the use of different weighting curves, such as A and G (Table). Results presented in Figs. 1 and 2 show the effect of wind direction on the noise directivity pattern (mainly leeward and windward as well as the difference resulting from different microphone heights above the ground level).

Results presented in Table and Fig. 1 reveal directional nature of wind power turbines as the sound sources. Noise propagated "with the wind" (downwind, behind an operating turbine) can be by from several to a dozen or so decibels higher with respect to this measured in a point situated in front of the working unit. The noise reveals also a low-frequency spectral structure, although

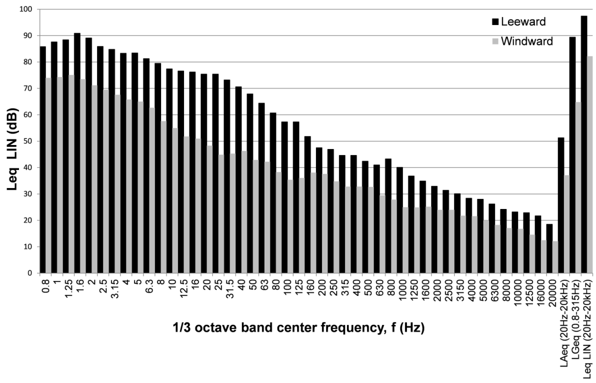

Fig. 1. Unweighted spectrum of the sound pressure level generated by wind power plant REPower MM92 for measurement points located to windward and leeward on the examined area. Microphone placed at 4 m a.g.l. (on a stand), wind speed 5.1 m/s at 10 m a.g.l..

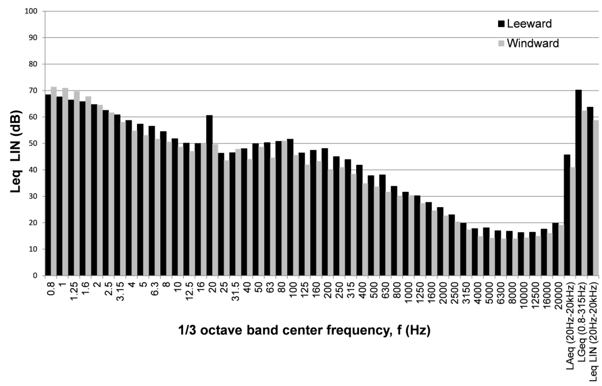

Fig. 2. Unweighted spectrum of the sound pressure level generated by wind power plant REPower MM92 measured in points to windward and leeward on the examined area. Microphone placed at 4 m a.g.l. (on a stand), wind speed 2.1 m/s at 10 m a.g.l.

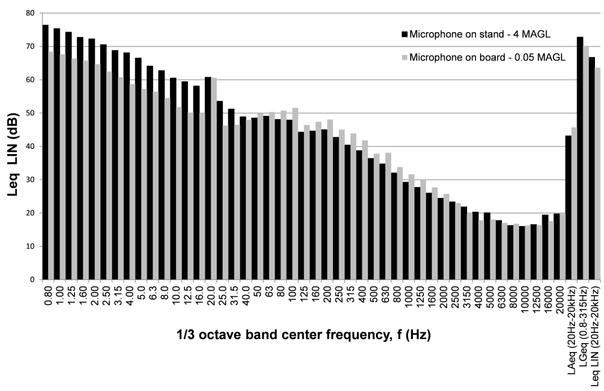

Fig. 3. Acoustic pressure level spectra in 1/3 octave bands: black bars —microphone at 4 m a.g.l. (on a stand); gray bars —microphone at 0.05 m a.g.l. (on the plate).

the acoustic pressure level values for low frequencies do not disclose presence of any infrasound above the hearing threshold (which is nearly 100 dB in the 10 Hz band).

Further, in Fig. 3, noise spectra measured with microphone located on the plate (at 0.05 m a.g.l.) and on a stand (at 4 m a.g.l.) are shown.

TABLE

Equivalent acoustic pressure levels: L_{LINeq} (unweighted), L_{Aeq} (A-weighted), and L_{Geq} (G-weighted) in selected frequency bands for REPower MM92 wind power turbine measured at leeward and windward points of the monitored area. Distance from the turbine tower base – 200 m; microphone position – 4 m a.g.l.; wind speed – 5.1 m/s at 10 m a.g.l.

Frequency band	L_{LINeq} (dB)		L_{Aeq} (dB)		L_{Geq} (dB)	
	Leeward	Windward	Leeward	Windward	Leeward	Windward
0.8–20000 Hz (full band)	97.4	81.6	–	–	–	–
0.8–16 Hz (infrasound band)	97.1	81.6	–	–	87.0	63.8
0.8–315 Hz (low frequency band)	97.2	81.6	–	–	89.4	64.8
20–20000 Hz (audible band)	80.5	54.0	51.3	37.1	–	–

It can be clearly seen from Fig. 3 that in the low frequency range, the acoustic pressure level is definitely higher than this at height of 4 m a.g.l. (the effect of wind), while on the plate, higher values were measured in the higher frequency regime (the effect of sound reflected from the plate). It can be therefore stated that placement of the microphone on a plate eliminates efficiently the effect of wind on measurement results in the low frequency range that could be misinterpreted as the ultrasound. However, there is still the problem of the relationship between the value measured on the plate and at height of 4 m a.g.l. that also depend on the wind speed an in the case of the study presented above varied from 1–2 dB(A) at slight breeze to 4 dB(A) at stronger wind.

In all probability, the most irritating feature of noise generated by wind turbines are the sound level amplitude modulations, i.e. the "swishing" noise. In turbines of newer generations, the sound falls in the band ranging from 250 Hz to 700 Hz, in older types it may exceed 1 kHz. This phenomenon is illustrated in Fig. 4 where it can be seen that in short time intervals (2–3 seconds), a periodical component with amplitude of about 5 dB appears in the A-weighted sound pressure level.

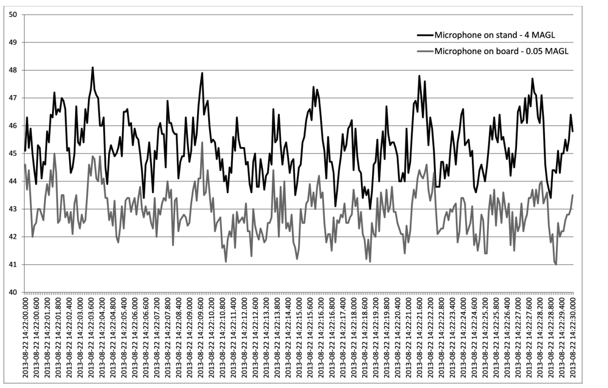

Fig. 4. Modulation of A-weighted sound pressure level (L_{Aeq}) for REPower MM92 turbine: black plot — microphone at 4 m a.g.l. (on a stand); gray plot — microphone at 0.05 m a.g.l. (on the plate).

5. Conclusions

Results of the research presented in this paper illustrate typical problems encountered in the course of preparing reports on environmental impact of wind power stations on acoustic climate in the environment including, first of all, the impact of directive pattern of noise emitted by wind turbine on such assessment both in the design stage and in the course of measurements and further, ambiguity of measurement results acquired according to (applicable) reference methodology [7], mainly in view of strong dependence of such results on prevailing wind velocity and direction.

The study has revealed also existence and significant fluctuation of tonal sound components that are more and more commonly praised as a dominant (apart from the low-frequency noise) source of acoustic annoyance caused by wind turbines. Examples quoted above include negative assessment of the effect of wind turbines on birds and bats. It has been also noted that such assessment fail to take into account the impact of noise, whereas in the case of investment of other types criteria similar to those applicable to assessment of noise arduousness to humans are used.

The problems related to the impact of wind turbines on acoustic climate pertain not only to land inhabited by people, but also to areas protected under the Natura 2000 scheme, mainly in view of absence of harmonized procedures applicable to preparation of reports concerning environmental impact of investments that would take into account typical conditions of operation of wind turbines, their location, and the type of noise generated by such devices. The necessity to work out relevant national-level documents that would establish conditions to be met by undertakings that either always have or may have a negative environmental impact, in accordance with the sustainable development principle and with consideration for social, economical, and environmental needs was many times praised at meetings of the Committee for Environmental Impact Assessments. It is worthwhile to point out that the prepared draft versions of related guidelines [3, 5] lack standardized procedures for determining the effect of wind turbines on the environment especially in scope of acoustic interactions that would take into account the operation conditions normal for this type of devices (strong wind), high altitude of the involved sound sources, and the type of noise emitted (tonality, amplitude modulation, and low-frequency noise).

As a particularly urgent issue, one has to consider the development of such measuring methodologies and assessment criteria for noise generated by wind turbines which would take into account specific operation conditions and features of the emitted sound. Independently, general methods applicable to assessment of the impact of noise on Natura 2000 areas should be worked out. In this context, there is an urgent need to continue research on the relationship between the noise and behavior of animals living in these protected habitats. Long-term monitoring studies should be a base for development of such assessment procedures and criteria.

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