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MEASUREMENTS OF NOISE FROM WIND TURBINES TAKEN IN SOUTHERN ITALY

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ABSTRACT

Electrical energy from wind turbines is a good alternative to the fossil fuel consumption for electricity generation. The use of wind energy would help reduce air pollution. One of the problems with wind turbines is the noise emitted by the towers, which can be divided into two components: a high-frequency component generated by the rotor and a medium-low frequency component produced by the rotation of the blades against the mast. This paper deals with the acoustic measurements of the wind turbines, which are characterized by different power and wind speed at the nearest sensitive receptors, such as residential properties. The measured values have been compared with the calculated noise levels in accordance with ISO 9613. The comparison showed a significant difference between measured and calculated values.

Keywords: *wind turbine, noise, acoustic annoyance.*

1. INTRODUCTION

The first wind towers to convert wind energy into electricity were built in the United States during 1950s and thereafter it spread rapidly during the 1970s, following the fossil energy crises. Nowadays, wind energy is the most competitive renewable energy source for electricity generation, helping to limit fossil fuel consumption and reduce the impact of air pollution. Wind energy contributes significantly to reducing the use of fossil fuels in the production of electricity, so wind power is an essential component of the green economy. The ability to use wind to turn blades, lift water or power millstones is a very old invention. The first windmills were built in the Middle East around 600 BC. In the Middle Ages this technology was introduced in Spain, Northern Europe and the Mediterranean islands. Windmills with cylindrical brick towers and blades made of wood and canvas can be visited as tourist attractions in Spain, Holland, Belgium and Sicily. The rapid growth of wind farms has led to the debate on their environmental impact, so much so that they are considered a new source of pollution. In Europe the largest concentration of wind farms is in the northern area. In Italy, the main areas with wind farms are located in the south, on the Apennine ridge, where wind speed is sufficient. In 2001, only 81 wind farms were built in Italy, with an power generation capacity of 664 MW, but in 2015, 2,734 wind farms were built, with an power generation capacity of 9,162 MW. Many wind farms have been built nearby existing residential properties, rising nuisance concerns for the occupants living in the surrounding areas [1-3]. Noise emission by the operation of wind turbines can cause sleep disturbance and other diseases, depending on time of exposure and noise level. According to the World Health Organization (WHO), thresholds for nuisance have been established in relation to night-time period. In particular, a limit of 30 dBA in bedrooms is considered a recommended limit to avoid sleep disturbance which may have a negative impact on health. A recent study compared the effects of the noise created by the wind turbines detected with a series of

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noise measurements, together with statistical surveys on the local population living near wind farms, with the noise generated by transportation. This study compares the effects of the annoyance created by the noise of wind turbines detected with a series of sound measurement, together with statistical surveys of the local population living near wind farms, compared with other anthropic noise (cars, trains, airplanes). The noise generated by the operation of the wind towers, with the same perceived sound level, is perceived more annoying than other anthropic noises (Figure 1). Usually, the noise emitted by a wind turbine is a broadband noise and it is concentrated in the frequency range between 300 Hz – 2000 Hz, where the human ear is most sensitive and therefore the individual feels more discomfort [4].

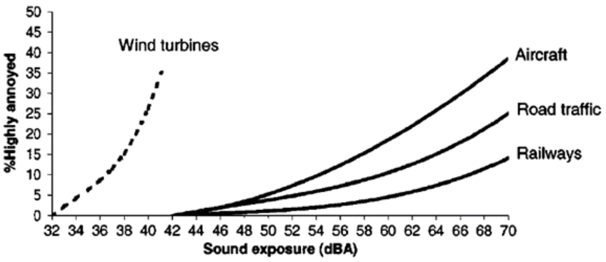


Figure 1. Comparison between the disturbance relationship for transport noise and the noise generated by wind turbines.

Specifically, noise from wind turbines is due to both the effects of air interaction during blades rotation and the systems inside the nacelle [5 -6]. The components of the generated noise are the following: airborne emission due to the blades' rotation, characterized by a broadband spectrum; and the emission produced by the electro-mechanical pieces, such as the generator, rotating gearbox, cooling systems and other components). This paper deals with the acoustic measurements of the noise generated by wind turbines of different power supply undertaken inside sensitive residential properties; the measured results have been compared with the outcomes of the numerical predictions calculated in accordance with ISO 9613. The two main scenarios (with the noise source turned on and off) have been compared with each other and with the predictions carried out by model simulations. This allowed the development of companies involved in the regeneration of wind turbines. The towers that were used in Northern Europe once installed in the new sites, produce less electricity and generate more noise due to the friction of the mechanical components that have worn out over time. Most of the wind towers installed in 2015 had a rated electrical output of less than 1.0 MW. Therefore, the number of installed wind towers with a small power rating increases significantly. Mini wind towers are those whose rated electric power is less than or equal to 200 kW (0.2 MW). This type of wind tower, despite their modest power, is the most widespread due to the simplified administrative procedures that must be respected and for the economy of the investment. These facilities are often installed near houses, generating conflicts between the population and the tower owners [8-9]. In the Northern European countries, a substantial renewal plan for existing parks is underway, which has identified several decommissioned wind turbines, which have therefore become available for possible use in the Southern European market [7-9].

2. IMPACT OF WIND TOWERS

The impact caused by the construction of wind farms include land use, visual impacts, noise and electromagnetic emissions, possible interference with the flora and fauna, as well as the presence of moving shadows due to the projection of the shadow of the rotating blades [4, 5]. Impact on flora is generally rather modest and limited to the construction phase of the wind farm, due to the excavations. However, there is the problem of impact on bird life. It is possible that birds during the migration season can fly into the moving blades of the towers. There can sometimes be electromagnetic disturbances during radio and television transmission, but this problem has been reduced with the use of glass fibre blades. Another problem is the low-frequency electromagnetic pollution generated by the passing of cable ducts near houses; laying the electric cables in tension at an adequate depth can limit these undesired effects. Wind towers are relatively tall and, being equipped with large rotating elements, attract the attention of the local residents, with them representing dominant elements on the perception of the landscape, while also creating a negative impact. The visual impact is mainly due to the considerable height of the wind turbines that are visible in any context and do not generally integrate with the landscape. Depending on the orography of the territory, they may be more or less visible. Obviously, the visual impact increases with an increase in height and the number of towers installed. A study highlighted how a few large turbines are preferred to numerous small turbines. To reduce the visual impact, some mitigation solutions can be used, such as the choice of lattice towers if wanting to reduce the visual impact from long distances (with the trusses often merging with the background), or tubular towers if wanting to reduce the impact at a short distance. Moreover, both lattice and tubular towers can be painted in neutral and anti-reflective colours in order to harmonize them with the surrounding environment. The effects that have not been studied in any particular detail but are still quite annoying, are those due to the prolongation of the shadows generated by the operating of the towers during sunrise and sunset (Figure 2).

Figure 2. Effects of shadow prolongation at sunrise and sunset

The shadow at either sunrise or sunset can cover a distance ten times greater than the height of the tower. Another possible problem for people living near the farms is the "flicker shadow" (Figure 3), the intermittent effect of the shadow, which occurs when the wind turbine is interposed between the sun and the observer. The shadow effect caused by the rotation of the blades is visible to the observer for a distance of about 300 m from the tower. This phenomenon does not occur when the blades are not rotating. This effect is highly annoying if it occurs inside the house, the intermittence of the shadow can create discomfort as well as loss of balance for residents of the surrounding areas. This negative effect can also be perceived by motorists who travel along the roads upon which the moving shadow is projected due to the rotation of the blades. When the towers are installed near roads, houses or places frequented by people, the calculation of the range should be estimated in case of accidental breakage of the rotating blade. If the detachment of the blade in rotation, due to the speed, this is thrown away as if it were a javelin. For wind turbines rated at more than 1.0 MW, this problem is very limited due to the low rotation speed. However, the problem occurs more frequently for systems with a power of 200 kW. The possible causes include the rotation speed of the blades (greater in the towers with a power of more than 1.0 MW), reduced maintenance of the farms and deterioration of the materials of which the blade is made. Such incidents are beginning to be reported more frequently.

Figure 3. Effects of "flicker shadow".

Furthermore, with a mini wind turbine in operation (power 0.2 MW), the blade rotation speed is about 30 rpm. The rotation of the blades is discontinuous, it depends on the instantaneous wind speed, and this generates an intermittent noise. Intermittent rotation at a speed of about 30 rpm can cause damage to the blade elements with the possible detachment of some components. Another noise component is due to the resonance generated inside the tower which can be schematized as a hollow cylinder closed at one end and open to the other.

3. ACOUSTIC IMPACT

Acoustic measurements were performed using a Class 1 sound level meter on a tripod. The sound level meter was configured to acquire the sound equivalent level of the "A" weighted sound pressure and the L95 statistical level, this sound pressure level is defined as the level exceeded for 95% of the observation time; in order to identify the presence of tonal components in the noise, a spectral analysis was carried out for normalized bands of 1/3 octave. The "A" -weighted filter (dBA) was used because the community's response to annoyance, due to wind turbine nose, is statistically related to "A"-weighted emission levels [23, 24]. The acoustic measurements were made by placing the sound level meter at about 1.6 m from the floor, and 1.0 m from the window. The window is open, it corresponds to the condition of maximum disturbance. The following regulatory approaches have been adopted to evaluate the annoyance produced by the operation of wind turbines in the living environment [10 - 13]:

- Differential criterion: the differential noise level is represented by the difference between the ambient noise level and the residual noise level; if the difference between the level of environmental noise (generated by the operation of the wind turbines) and the residual level (wind turbines turned off) is less than 5 dBA by day and 3 dBA by night, noise generation by wind turbines is considered negligible.
- Limit of "normal tolerance". Background noise (L95) is evaluated when the wind turbines do not work, and the equivalent level is evaluated when the wind turbines are in operation. The limit of normal tolerability is exceeded when the sound emissions are 3 dB above the background noise. The background noise is the percentile value L95, that is the value that is exceeded 95% of the time, therefore equal to the almost minimum value of the instantaneous sound level.

The houses where the acoustic measurements were carried out are located in a small rural municipality in Campania (Italy), the area is a plateau within a large basin at about 700 m above sea level, located in the central area of the Italian Apennines. The wind turbine consisting of a tubular tower and three horizontal blades. Blades began to move with wind speed around 2.5 m/s; and the rotation is stopped, for safety reasons, for wind speeds around 25 m/s. The highest electric power production starts for wind speeds above 15 m/s. A neglected aspect regarding the emission of noise by small wind turbines with a cylindrical tower is that the noise emitted is not only due to the rotation of the blades or to the noise of the systems in the spacecraft. The emission of the noise is a much more complex phenomenon, in fact to emit the noise is also the entire tubular structure of the tower put into vibration by the rotation of the blades; this effect does not manifest itself for large turbines because the thickness of the tower part is high and does not generate vibration effects. Furthermore, another component of noise is due to the resonance generated inside the tower which can be represented as a hollow cylinder closed at one end and open at the other.

A series of acoustic measurements were performed to assess the noise level introduced into the living environment, generated by the operation of the wind turbine. Measurements were performed with the windows open in maximum disturbance condition. Several series of measurements were performed corresponding to two operating conditions of the wind turbine (ON, OFF). Figure 4 shows a typical measurement sessionries with the time history of the measured sound pressure level (dBA).

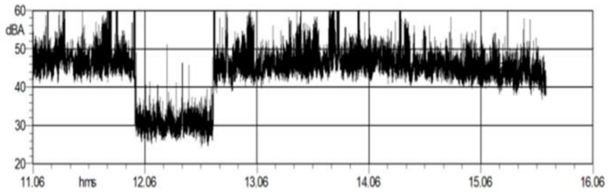


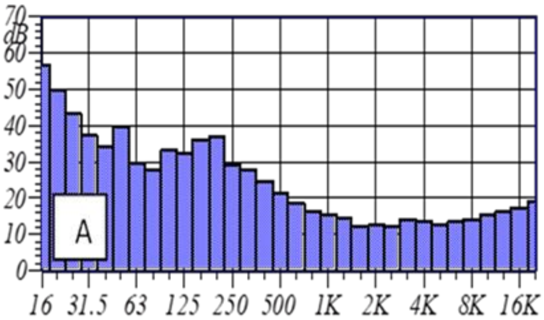
Figure 4. Time history of the measured of the sound pressure level (dBA) for two operating conditions (ON, OFF) performed in some measurement session.

When the wind tower is off, the sound pressure level of the residual noise and the background noise are significantly lower. While the tower is in operation the measured sound pressure level increases. Therefore, the operation of the tower involves an increase in the sound pressure level. Table 1 shows the measured values of average wind speed, equivalent sound pressure level (LeqA, dBA).

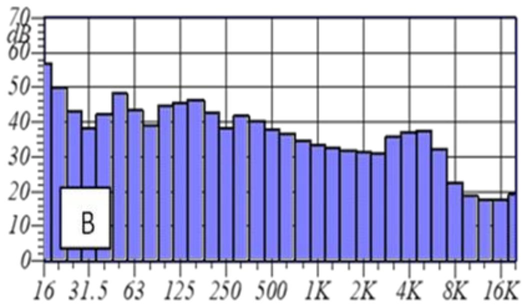
Table 1 – Summary of measured values

Wind Turbine power, MW	Average wind speed, m/s	Distance source - receiver, m	Sound pressure measured Leq, dBA
3.0	10	450	52
0.20	12	250	50
3.0	9	250	45
1.0	15	200	52
1.0	8	100	50
3.6	8	210	48
1.0	10	350	47
0.2	8	200	45

During the measurement sessions the wind speed was acquired from a meteorological station located near the house. The measurements were not performed when the wind speed was above 20 m /s. For most of the acquisition time it was dedicated to the condition in which the tower is in operation, and in the condition in which people complained of the greatest disturbance (annoyance). When the wind turbine is off, the residual noise level, measured inside home, is 30 dBA, while with the system in operation the measured sound pressure level is around 40-50 dBA. Therefore, in the dwelling considered the tower's functioning involves an increase in the sound level of about 10 dBA compared to when it is off. Figure 5 shows the frequency trend of the sound level measured when the wind turbine is off (A), and when the system is in operation (B). When the wind turbine is in operation the sound contributions emitted are included in a range from 63 Hz to 4.0 kHz.



Frequency, Hz



Frequency, Hz

Figure 5. Average frequency spectrum of the measured sound levels in 1/3 octave band between (dB Lin) for several measurement sessions (A) tower off, (B) tower on.

4. SOUND PROPAGATION SIMULATION MODELS

One of the problems encountered during the installation of a wind tower is the theoretical assessment of the noise entering the residential environment, as it is necessary to establish in advance whether the installation of the wind tower will cause disturbance to the residents living in the chosen area. The most used model is based on ISO 9613-2: 2006 "Acoustics - Sound attenuation in outdoor propagation". This regulation considers the sound source points-forms. A wind turbine is a complex system that can be considered a point sound source only when there is a large distance between the source and the receiver. For the determination of noise levels inside a receiver point, the standard ISO 9613-2 provides a theoretical method to evaluate the sound attenuation, with the source-receiver distance, in outdoor propagation [14-16]. The standard calculates the equivalent sound pressure level (Lp, dBA), assuming that meteorological conditions favor sound propagation (propagation downwind or in conditions of moderate inversion on the ground), by applying the following relationship:

$$Lp = Lw + DI\theta - Adiv - Aatm - Agr - Abar - Amisc$$

Where:
Lp: sound pressure level (dBA);
Lw: sound power level (dBA);
Diθ: directivity;
Adiv: attenuation due geometric divergence;
Aatm: attenuation due to atmospheric absorption;
Agr: attenuation due to the ground effect;
Abar: attenuation due to a barrier;
Amisc: attenuation due to foliage, industrial sites, housing.

The application of the calculation model of noise propagation appears to be precautionary, i.e., it provides an overestimation of the levels, when considering only the attenuation of the noise caused by the geometric divergence, not considering the other attenuating factors such as atmospheric absorption, as well as the presence of obstacles and vegetation. Numerical simulations based on engineering approaches are in many cases a rapid application. So, in a simplified way, the sound pressure level is given by the following formula:

$$Lp = Lw - Adiv$$

Here:

$$Adiv = 20\,Log(D) + 11$$

D is the distance between the sound source and the receiver. The theoretical assessment of the sound level due to the propagation of the noise produced by the operation of the wind turbines was carried out in compliance with the ISO 9613 standard. The calculation forecasts are based on the simulation of the wind turbine as a point sound source and on the attenuation due to the open window, estimated at 4 dB. Table 2 shows the summary of calculated values and the difference between calculated and measured values.

Table 2 – Summary of calculated values

Sound Power Lw, dBA	Distance source - receiver, m	Sound pressure measured Leq, dBA	Sound pressure calcualted Lp, dBA	Difference
104	450	52	36	16
100	250	50	37	13
104	250	45	41	3
104	200	52	43	9
100	100	50	45	5
106	210	48	44	4
102	350	47	36	11
100	200	45	39	6

The simulation model therefore underestimates the noise level inside a house. The theoretical relationship for the evaluation of the noise introduced in a house due to the functioning of a tower, applying the ISO 9613 standard; in the hypothesis of point source. When using the ISO 9613 standard this does not provide a correct indication of the estimated theoretical level inside a dwelling.

5. NEW PREDICTION METHODS

Considering the discrepancies between the values obtained from the ISO 9613 theory and those of the experimental results which, although both can be optimized, could hardly converge, it is clear that the propagation of the noise produced by wind turbines is rather complex to simulate and presents wide variations in input even at the same wind speed, variations that depend on the aerodynamic noise generated but also on meteorological parameters such as the temperature gradient, the wind speed profile, the wind direction and turbulence. Both the ISO 9613-2 model and the Nord2000 for example predict the average sound pressure levels in downwind conditions, but fail to predict the levels in upwind conditions. A theoretical-experimental analysis is currently underway for new forecasting methodologies based on a scientific work and the experience acquired on over 350 wind farms with the OTL - Suite v4.0 software, which uses acoustic geometry based on the propagation of waves which preserves the wave nature of sound propagation and takes into account atmospheric refraction. To date it cannot be said that there is a practical engineering model that can take into account all phenomena simultaneously, but it is also true that computational advances made it possible not only to perform long-range sound propagation calculations but also to develop calculation including the following:

- reflection coefficient for spherical waves,
- multiple diffractions,
- atmospheric refraction and turbulence,
- atmospheric absorption.

For example two separate models are used for refraction: one by “L'Espérance, Herzog, Daigle, & Nicolas, 1992” [18] for downwind and upwind refraction and the other by “West, Walkden, & Sack, 1989” [19] for calculations in shadow areas in order to model sound transmission in an inhomogeneous atmosphere with linear sound velocity profiles or for linear approximations of logarithmic sound velocity profiles.

6. THEORY VERSUS MEASURED DATA

The experimental study consisted of 6 wind turbines (hub height 80 m, rotor diameter 90 m) and the recorded meteorological measurements were: wind speed and direction at heights of 2 m, 10 m, at hub 80 m; temperature, humidity and atmospheric pressure at heights of 2 m and 10 m. The microphone positions were at a height of 1.5 m and at horizontal distances of 150 m and 500 m from the wind blades; Measurements were made in 1/3-octave bands and presented in L_{eq} for a horizontal radius of 150 m from the wind turbines and L50. The wind turbine is modelled as a point source whose sound power level is taken from the available nameplate data. Among different cases studies, we have the following parameters for WTN Case-1:

Source dist., 80 m; Receiver height, 1.5 m, Distance 150 m.
Ground temperature 10.7 °C, Temperature at (10 m) 10.7 °C.
Wind speed altitude (at 10 m), 6.8 ms^{-1}
Wind direction to Sound-to-sound direction Downwind
Roughness constant: 0.05 m, shear factor 0.05

Soil flow resistivity: 225000 Pa s m^{-2}.

The excess attenuation is first calculated in narrow frequency bands starting from 20 Hz in 5 Hz steps up to 500 Hz, with steps going from 20 Hz to 10 kHz. The frequencies of the excess attenuation are then combined in the centre frequencies of a 1/3 octave spectrum from 25 Hz to 10 kHz. The direct sound (which includes the characteristics of the source) is then added to the Excess Attenuation in the 1/3 octave spectrum to obtain the sound pressure level which is then reported in 1/1 octave and in dBA.

A comparison for WTN case 1 shows good agreement between calculations and measurements at a distance of 150 m from the wind turbine, with almost the same minimum of interference at around 125Hz. This means that the sound power level taken as input data and the propagation model work well, even in the point source approximation.

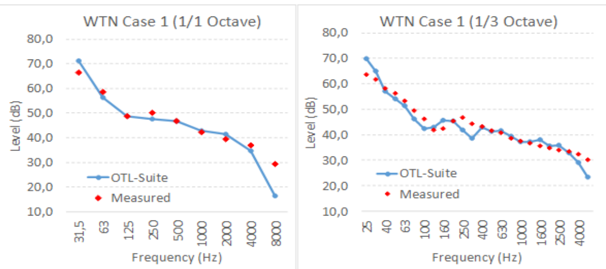


Figure 6: Measured and Calculated Noise Level for WTN Case 1, downstream case at 150 m.

7. CURRENT RESEARCH

The research currently underway aims to perfecting the methodology for forecasting the noise produced by the WTNs by introducing different parameters of sound propagation and weather conditions which must be accurately measured "in parallel" with the acoustic measurements. The study in [17] demonstrated good agreement between calculation and measurements in downwind cases and acceptable in upwind conditions. Key points are the knowledge of meteorological data such as the wind speed profile and the temperature gradient to be evaluated by means of two weather forecasts at 2 m and 10 m height [18]; a good compromise of the detection frequency is one calculation for each 10-minute sample of weather data. As demonstrated in the validation of the reference Harmonoise model, a significant discrepancy between the experimental data and the theoretical data obtained with ray-models is the approximation in the calculation of the sound velocity profiles, even if the calculation time must be taken into account. Future considerations are focused on the study of subsonic noise propagation, noise sources modelled as mobile dipoles and quadrupoles for more realistic calculations, calculation of modulation effects, the transition from the Leq indicator in dBA to a more correct evaluation of the annoyance value through appropriate auditory models.

8. DISCUSSION

As we have seen the sound level measurements in the house provides a level of 50 dBA. From the comparison with the theoretical values estimated by the model there is a difference from 4 to 16 dBA between measured and calculated. The simulation model therefore underestimates the noise level inside a house. The theoretical relationship for the evaluation of the noise introduced in a house due to the operation of a tower, applying the ISO 9613 standard in the hypothesis of point source. It was found that the theoretical relationship underestimates the measured value of the sound pressure level inside the house. When using the ISO 9613 standard this does not provide a correct indication of the estimated theoretical level inside a dwelling. The theoretical assessment of the sound level due to the propagation of the noise produced by the operation of the wind turbines was performed in compliance with the ISO 9613 standard. The calculation predictions are based on the simulation of the wind turbine as a punctiform sound source and on the attenuation due to the open window, estimated at 4dB. The variety of case studies, characterized by a different distance between the source and the receiver, has shown that the forecasts underestimate the actual noise levels emitted by wind turbines. It should be noted that for the theoretical estimation of the sound pressure level, a sound power value Lw taken from the wind turbine technical sheets is used. Furthermore, one of the main factors which the legislation will have to take into account is the wear of the rotating elements and the effects of scheduled maintenance, which in reality will lead to an increase in the noise levels emitted compared to the initial measurements carried out under new wind turbine conditions. This result highlights the limitations of the existing theoretical standard (ISO 9613) which must be implemented with further considerations in order to obtain results that are close to the practical measurements.

9. CONCLUSIONS

The theoretical assessment of the sound level due to the propagation of the noise produced by the operation of the wind turbines was carried out in compliance with the ISO 9613 standard. The calculation forecasts are based on the simulation of the wind turbine as a point sound source and on the attenuation due to the open window, estimated at 4 dB. The variety of case studies, characterized by a different distance between the source and the receiver shown a clear underestimate of the Lp emitted by WTN. Nevertheless, to mention that a sound power (LW) was taken from technical data sheets, while for simplicity of calculation, not all attenuations envisaged by the standard have been considered, the significant underestimation of Lp values requires further research as for example the short introduction on Chapters 6, 7 and 8 about propagation models and meteorological boundaries conditions. Furthermore, one of the main factors that the legislation will have to take into account is the wear of the rotating elements and the effects of scheduled maintenance, which in reality will lead to an increase in the noise levels emitted compared to the initial measurements carried out in wind generator conditions new. This result highlights the limits of the theoretical standard (ISO 9613) which must be implemented with further considerations in order to produce results close to the acoustic measurements.

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