Advances in Measuring Noise from Wind Turbines

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WHY DO WE NEED TO MEASURE WIND TURBINE NOISE?

The US Department of Energy has examined a scenario that has wind turbine technology providing 20% of the electricity for the US by 2030. To fulfill this vision, we must prepare the next generation workforce to meet the needs of the wind turbine community. This article provides an overview and reference resource on various types of wind turbine noise measurements for those working on various aspects of wind energy, especially those starting their careers in wind energy or who are transitioning their skills to the wind industry.

We must measure wind turbine noise for (i) compliance and (ii) to develop methods to redesign wind turbines that emit less noise. Compliance regulations vary by location. For example, US wind farms must comply with US Federal Environmental Protection Agency and Occupational Health and Safety Guidelines and be approved by state and local regulators. Recent news stories have indicated that the turbine noise levels have become a factor in deciding whether to approve these installations because they affect the quality of life for nearby residents.

For research and redesign purposes, we need detailed measurements of the wind speed, acoustic directivity, source location and aerodynamics of the flow over turbine blades to uncover the physics and redesign turbines for low noise (see Ref 1-7).

BASIC ACOUSTICS TERMINOLOGY

WHAT IS ACOUSTICS?

Acoustics is the science of sound waves. Sound is the sensation produced in the ear by very small pressure perturbations in the surroundings. Noise is unwanted sound (could be subjective) and excessive noise is known to affect humans (health, behavior, productivity), and the final result can range from mere annoyance to irreversible hearing loss.

The difference between acoustic waves and other types of mechanical waves is that acoustic waves are longitudinal—direction of motion of particles is parallel to the direction of wave propagation, and the wave consists of compressions and rarefactions of the medium.

SOUND PRESSURE LEVELS

The range of sound pressure of most interest varies from 1 x 10^{-9} psi (the threshold of hearing) to 15 psi—10 orders of magnitude. A log scale is useful in condensing this wide range so that it is easier to manage. Sound is usually quantified as Sound Pressure Levels expressed in decibels (dB)

SPL = Sound Pressure Level

$$= L_p = 20\mathrm{Log}_{10}\left(\frac{p}{p_{re}}\right)$$

P = root mean square (rms) sound pressure (pa or N/m^2)

P_{re} = international reference pressure = 2 x 10^{-5}pa (20μPa)

SPL is expressed in decibels (dB).

SOUND POWER AND INTENSITY

We report sound pressure level and sound power level in decibels (dB) relative to a standard reference level.

Sound power is a characteristic of the source and is the rate at which acoustical energy radiates from a source. The sound power level from a source of constant power is thus independent of space and time. In contrast, the sound pressure level depends on the location of the measurement.

The sound power level is given by

$$L_W = 10\text{Log}_{10}\,(W/W_{re})$$

where W is the acoustic power being considered and W_{re} is the reference power (10^{-12} Watts).

Sound intensity is defined as the acoustic power passing through unit area.

I = W/A, where W is the acoustical power of the source and A is the surface area.

For spherical radiation, $I = W/4\pi r^2$, where $4\pi r^2$ is the surface area of a sphere.

FREQUENCY AND SPECTRA

For waves that repeat with time (periodic waves), the time, T, required for one complete cycle is called the period of oscillation. The frequency (Hz) is the reciprocal of the period ($f = 1/T$).

We can represent spectral data that indicates how the measured sound distributes over the frequency spectrum as either narrowband spectra (where tones can be spotted) or 1/3rd Octave spectra. Octave and 1/3rd octave bands are geometric scales used by acoustics engineers. The bandwidth is given by $(f_{n+1} - f_n)$ where f_n and f_{n+1} are successive band limits (for upper and lower bands). These bands are geometrically related by $(f_{n+1})/(f_n) = 2^k$. If k = 1, the bands are known as octave bands. When k = 1/3, the bands become 1/3rd octave bands. The center frequency of the band is given by $f_c = (f_{n+1} \times f_n)^{1/2}$.

We often use frequency weighting procedures such as A-weighting where the signal is progressively attenuated towards the low and high ends of the audible frequency range. The A-Weighted scale closely follows the frequency response of the human ear and therefore plays a prominent role in noise control.

BROAD CLASSES OF MEASUREMENTS FOR WIND TURBINES

There are two classes of measurements for wind turbines.

(i) Standard acoustic measurements using individual microphones that conform to International Standards such as IEC 61400. This measurement type helps determine if a wind turbine installation conforms to published National and local regulations.

(ii) Research measurements made to identify dominant sources associated with a wind turbine and to determine the effectiveness of wind turbine noise suppression technologies. For example, these measurements may indicate the dominant noise sources, their location, and their origin. Based on source location and frequency, we can answer questions such as “is this aerodynamic noise”? or “is this noise produced by mechanical components of the turbine”? (Ref 8-11).

We make conventional acoustics measurements of test articles in anechoic chambers where we can isolate the noise from the turbine with no contributions from other sources or from reflections. However, the large scale of a wind turbine makes it prohibitively expensive to test within an anechoic chamber. In addition it is extremely difficult to asses the effect of wind, wind direction, and gusts in a wind tunnel. One approach that overcomes these difficulties is to make measurements on-site using a phased array. Oerlemans (Ref 1, 2, 7, 12, 13) and Dougherty (Ref 14) described examples and techniques for phased arrays. According to Dougherty (Ref 14), "a number of microphones can be used together to extract the desired source location and level information in the middle of noisy, reverberant situations."

CONVENTIONAL ACOUSTIC AND WIND SPEED MEASUREMENTS

An International commission has established a standard, IEC 61400 (Ref 8), that ensures consistency and accuracy in measuring and analyzing acoustical emissions by wind turbine generator systems—for guidance in measuring, analyzing, and reporting complex acoustic emissions from wind turbine generator systems. This standard provides procedures expected to provide accurate, replicable results. The standard specifies instrumentation and calibration requirements to ensure accuracy and consistency of acoustic and non-acoustic measurements. It also specifies non-acoustic measurements required for defining the atmospheric conditions relevant to determining the acoustic emissions. To account for the size of the wind turbine under test, we use a reference distance *R*o based on the wind turbine dimensions. We measure with a microphone on a board placed on the ground to reduce the wind noise generated at the microphone and to minimize the influence of different ground types. We measure sound pressure levels and wind speeds simultaneously over short periods and over a wide range of wind speeds. We convert measured wind speeds to corresponding wind speeds at a reference height of 10 m. We determine and use sound levels at standardized wind speeds of 6, 7, 8, 9, and 10 m/s for calculating apparent A-weighted sound power levels. We determine directivity by comparing A-weighted sound pressure levels at three other positions around the turbine with those at the reference position.

IEC 60804 provides instrumentation guidelines. The equipment should meet the guidelines of a type 1 sound level meter that has a microphone diaphragm no greater than 13 mm in diameter. In addition to the requirements given for type 1 sound level meters, the equipment shall have a constant frequency response over at least the 45 Hz to 11 200 Hz frequency range. The standard also requires the test anemometer and wind direction transducer to be mounted in the upwind direction of the wind turbine at a height between 10 m and the center of the rotor. Researchers can determine wind speed from either (i) electrical output and power curve or (ii) a more direct measurement using an anemometer. Method (ii) is the preferred approach for certification measurements.

One should note that the power curve relates the power to the wind speed at hub height. For most wind turbines, we can determine wind speed from the measured electric power. Correlation between measured wind speed and measured electric power is very high up to the point of maximum power. The standard also requires that wind speed be obtained from measurements of the produced electric power using a traceable power versus wind speed curve, preferably measured according to IEC 61400-12 and preferably for the same turbine or, otherwise, for the same type of wind turbine with the same components and adjustments. However, note that during background noise measurements, we must measure wind speed with an anemometer at a height of at least 10 m.

STATE-OF-THE ART TECHNOLOGIES FOR STUDYING WIND TURBINE NOISE

Research measurements for wind turbine noise involve both flow and noise. Since flow over turbines relates to aerodynamic noise, we also need flow measurements such as detection of flow separation using thin film sensors or flow measurements to detect vortices shed by the cylindrical tower or to detect blade tower interaction. Instrumentation is available from many companies such as Dantec Dynamics for wind turbine optimization based on airflow.

Research measurements using microphones involve multi-sensor techniques, including measurements of modes of blade flutter using modal analysis. An example of such a measurement can be found in a B & K brief (Ref 11)) where researchers used a number of B & K 4507B accelerometers to study blade flutter. We can make simultaneous acoustic measurements using microphones such as the B& K 4176 (1/2" diameter) in conjunction with the Pulse system. Other microphones, especially for array applications where a large number of microphones are necessary, include the LinearX M51 and Panasonic WM-61.

Phased arrays have been used extensively in radio astronomy and radar systems and applied them for source location of aircraft, sonar array, and wind turbine noise. There are two main types of phased arrays, also called beamformers (time domain and frequency domain). Used with a large number of microphones, beamforming can reveal information about the strength and location of sources—the following sections provide two examples that use phased arrays for wind turbine noise measurements.

PHASED ARRAY EXPERIMENTS CONDUCTED IN THE NETHERLANDS

One example of phased array measurements relates to work of Oerlemans et al. (Ref 1, 2, 12)–collaboration between the National

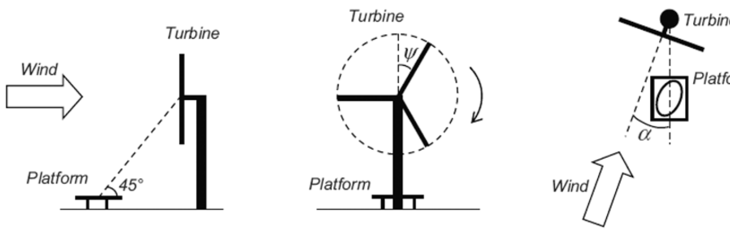

Figure 1 (a). Wind turbine schematic showing measurement locations

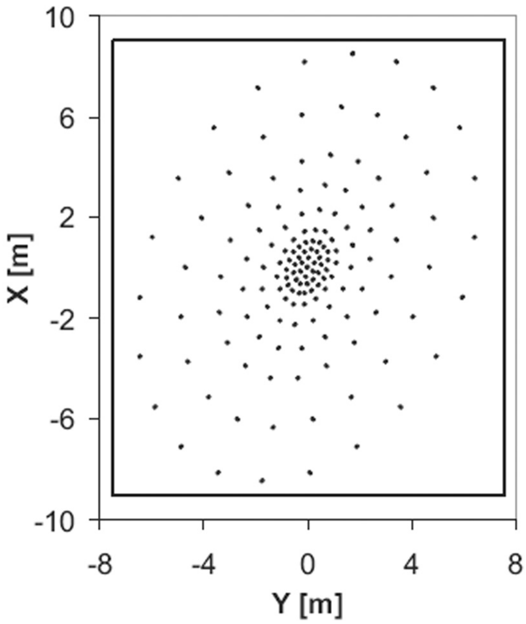

Figure 1 (b). Configuration of microphones for phased array measurements.

(Figure 1(a,b) from Oerlemans et al. (Ref. 2), used with permission

Aerospace Laboratory (Netherlands) and the General Electric (GE) Company. The authors carried out acoustic measurements on a three-bladed turbine, using a large horizontal microphone array positioned at a distance of about one rotor diameter from the wind turbine. The microphone array located and quantified noise sources in the rotor plane and on individual blades. Measurements were carried out on a 2.3 MW prototype test wind turbine. It had a rotor diameter of 94m and a tower height of 100m. The turbine was located on the Netherlands Energy Research Foundation test site in Wieringermeer. A control system adjusted the RPM and blade pitch depending on wind speed measured at the Nacelle. The turbine also had a yaw mechanism that automatically turned the rotor against the wind.

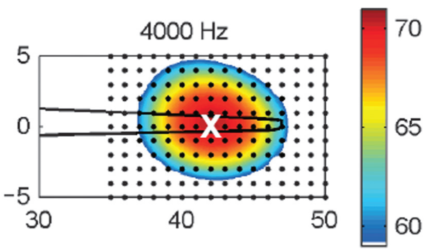

Figure 2. Location of sound produced by a whistle mounted on one of the turbine blades

To evaluate wind turbine noise reduction methods, they tested a rotor that had three different blades. One was the standard baseline blade, the second had a serrated trailing edge, and the third was a SIROCCO blade. The SIROCCO blade was similar to the baseline blade, but the outer 30% had a new airfoil section. Fig. 1(a) shows the location of the acoustic array relative to the wind turbine. An acoustic array consisted of 148 Panasonic WM-61 microphones mounted on a wooden platform (16 x 18 m^2). The microphone array had an elliptical configuration (see Fig.1(b)).

To assess the accuracy of the source localization technique, researchers attached a whistle to one blade at a position unknown to the acoustic test team. The test team then determined the blade to which the whistle was mounted and the exact whistle position on the blade (see Fig. 2). Oerlemans et al. (Ref 1) took 600+ measurements over four weeks. They followed the IEC standard 61400-11 that suggested measurements at 10 m height at wind speeds between 6 and 10 m/s. Since the array position was fixed and the wind direction varied, they made both upwind and downwind measurements. During field tests, the three different blades could be distinguished by the swishing noise produced during the passing of each blade.

Figure 3 shows the overall sound pressure level (OASPL) measured using a single microphone as a function of rotor azimuth angle. The measurement was made using a single microphone at the center of the array; OASPL levels are A-weighted. The levels were summed in the frequency range from 250 to 800 Hz to focus on low frequency noise. Noise reductions produced by blade treatment are clearly visible in the figure.

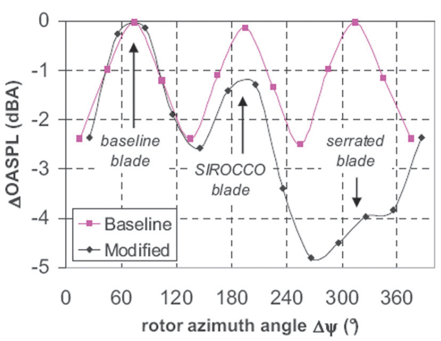

Figure 3. Comparison of relative overall sound pressure level for various types of wind turbine blades. (Figures 2 and 3 from Oerlemans et al. (Ref. 2), used with permission

Figure 4 shows average blade noise spectra at 10 m/s wind speed for various frequencies, where there is broadband noise reduction (except at the highest frequency band), while at 7 m/s there is a significant increase at higher frequencies. Averaged over all wind speeds, with serrations one can halve the noise (3 dB) without energy loss.

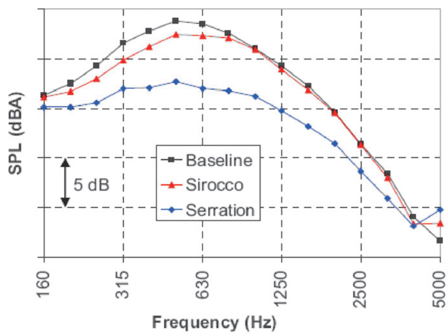

Figure 4. Spectra for various types of wind turbine blades

Figure 5 shows the noise benefits of blade treatment over a range of wind speeds. The OASPLs here are summed between 160 Hz and 5kHz. In the paper by Oerlemans et al. (Ref 2), the authors show through acoustic source maps that the dominant source of noise was trailing edge noise from the outer 25% of the blade. In addition, both modified blades showed significant trailing edge noise reduction at low frequenices and displayed a noise increase at high frequencies (associated with the blade tips).

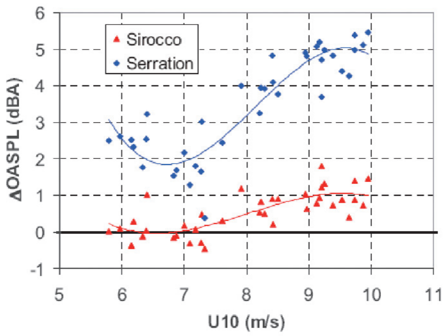

Figure 5. Effect of wind velocity on the overall sound pressure level for various types of wind turbine blades. (Figures 4 and 5 from Oerlemans et al. (Ref. 2), used with permission

PHASED ARRAY EXPERIMENTS CONDUCTED USING A ROAD VEHICLE MOUNTED SYSTEM IN THE US

The second example of phased array measurements is based on data that Robert Dougherty of OptiNav acquired. These phased array measurements were made using a road vehicle mounted system. He performed measurements using OptiNav Array 24 that is a beamforming system with 24 Panasonic WM-61 microphones mounted in a plane with an aperture of 0.7 m. The processing software, Beamform Interactive, provides several options. One is TIDY, a new deconvolution algorithm that generalizes CLEAN-SC (Ref 15) to the wide band, time-domain case. TIDY dramatically improves the low frequency resolution of a phased array. In some cases, resolution is 10 times better than the classical limit.

Figure 6. The Optinav array 24 mounted on a road vehicle. (Courtesy of R.P. Dougherty (Optinav), used with permission)

He investigated wind turbine noise by mounting a prototype Array 24 on a Subaru (Fig. 6). He drove the system to the PacifiCorp's Marengo Wind Facility (Columbia County, WA) to image 1.8 MW Vestas V80s. He acquired data sets

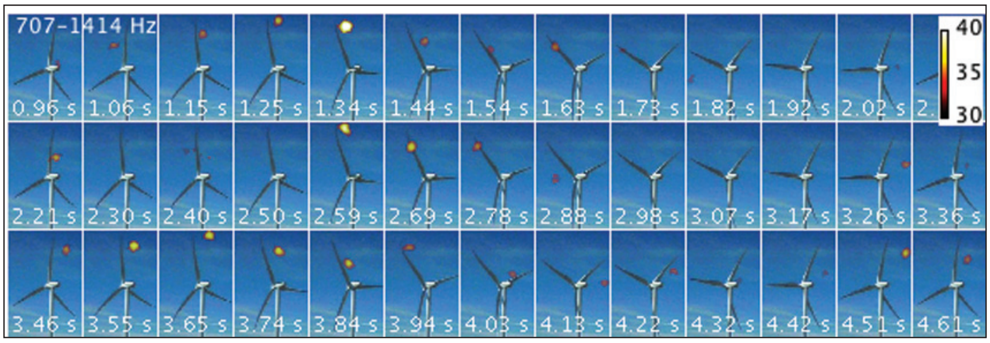

Figure 7: Time sweep for one revolution for the 1 kHz octave band. TIDY processing

by parking on a county road near a wind turbine at an angle such that the turbine appeared in the array's video camera, turning off the car engine, and recording for approximately 10 seconds. He obtained a GPS location for later identification of a particular wind turbine. He performed beamforming immediately in some cases to verify system function.

Fig. 7 shows sample results. He applied TIDY in all cases. Fig. 7 is a time sweep representing one revolution of Turbine M72 from a distance of 258 m (measured distance by scaling the height of the mast in the video images and verified them by consulting a map.) The analysis represents the 1 kHz octave band: 707-1414 Hz. The noise source locations in this band appear mainly behind the blade trailing edge, at the mid to outer radius, at the top of the blade rotation. The production of sound while the blades were passing though a certain arc created a periodic swishing—clearly noticeable at site.

Fig. 8 gives time-averaged data (about 1.75 revolutions) for the 500 Hz, and the 1, 2, and 4 kHz octave bands. Noise originating from the nacelle can be seen the in the 500 Hz and 4 kHz bands. Aerodynamic noise appears in all but the lowest bands.

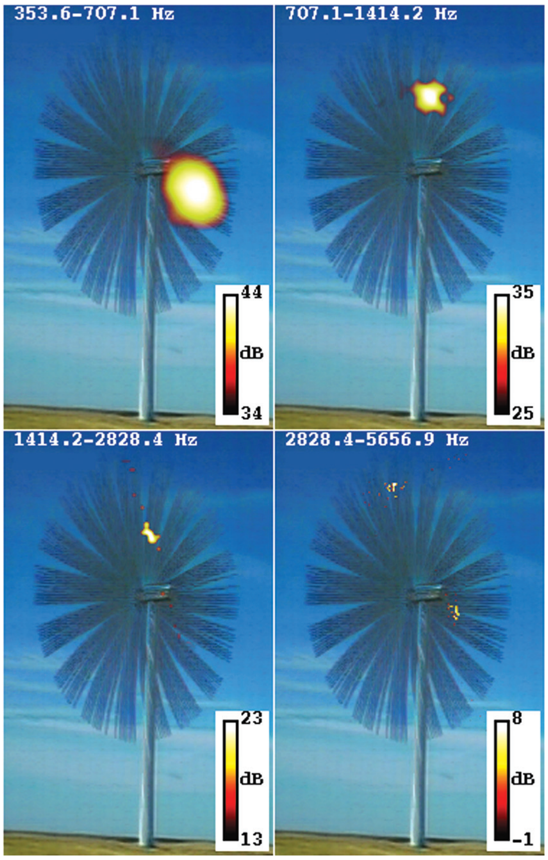

Figure 8. TIDY octave band images for about 1.75 revolutions. (Figures 7 and 8 courtesy of R.P. Dougherty (Optinav), used with permission)

Fig. 9 shows a wider field of view from the same array location as the previous figures to include the contribution from Turbine M71 (395 m from the array) in addition to M72.

Data produced in such experiments can validate computational aeroacoustics programs such as the one in Ref. 16. Ref. 17 provides background on computational aeroacoustics.

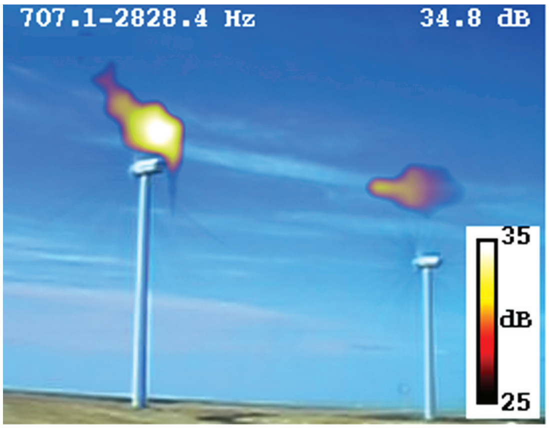

Figure 9. *Two wind turbines: 258 m and 395 (Courtesy of R.P. Dougherty (Optinav), used with permission)*

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TURBINE NOISE WON'T AFFECT PROPERTY VALUES

The U.S. Department of Energy's (DOE's) Lawrence Berkeley National Laboratory, with funding from the DOE's Wind and Hydropower Technologies Program, has concluded after intensive research that wind turbines have very little effect on property values. One of the biggest criticisms of wind power has been that the turbines are noisy and unsightly, and will cause properties that they are on or near to lose considerable value. The Laboratory used eight-point hedonic statistical analysis to analyze home and property sales prices of 7500 real estate transactions entered into from 1996 through 2007 which involved the buying and selling of real estate within a 10 mile radius of an existing wind turbine array. One home was only 800 feet away from a wind turbine facility. The conclusion was that while it is probable that there are some people who would never wish to have to look out on a wind turbine array, leading some small percentage of property values going down, there is no significant negative impact at all on the larger real estate value picture concerning situations where wind turbine arrays are within sight of a property.

CHURCH AND STATE

A church has won an increasingly bitter legal fight over its right to amplify sermons and singing during services. Lambeth council threatened the All Nations Centre in Kennington, London, with prosecution and served it with a noise abatement notice after receiving complaints from neighbouring families. The church, which has 600 members, claimed victory after the council withdrew the order just hours before the case reached court. Senior pastor Abraham Sackey said the council had ulterior motives after the notice was served without warning or discussion. He said: "It had nothing to do with noise but rather was further evidence of the ongoing campaign of religious hatred and intimidation against evangelical Christians. The council is driving us out and we feel harassed." The authority denied the claim. The centre, which has been at its current location for 45 years, received the backing of its local MP, Kate Hoey. She said: "They have been serving the community for many years, consistently helping to improve the quality of life and overall well-being of people. So it was with surprise and concern that I learned they were served with a noise abatement notice." Residents, however, say the noise remains a problem and called for the council not to give up trying to control it. Neighbours said it was not the singing that concerns them but rather the noise made outside the church.

WHEELS WITHIN TURBINES

A draft proposal is under consideration in Crescent City, California, to allow small wind energy systems within the city limits. However, officials have realised that before the proposal can be moved forward, the city's noise ordinance will have to be revised: it includes no provisions for the noise generated by wind turbines.

NOISE COMPLAINTS PUSH UP COSTS ON LA RAIL LINE

An effort to build a new commuter rail line in Los Angeles has hit a snag. A permit for construction work to continue around the clock was revoked for one segment of the Expo Line because of noise complaints. The decision by the Los Angeles Police Commission means no work on the segment can be done overnight. The $862-million line is already a year behind schedule and $220 million over budget. The line initially will run from downtown Los Angeles to Culver City but eventually it will be extended to the beach town of Santa Monica.

MORE EMPLOYER NEGLIGENCE

A construction worker who suffered deafness after working for Sheffield Council 'hole in the road' and the Hallamshire Hospital in the 1960s and 70s, has won compensation. Alan Fox, aged 64, from Gleadless, has been awarded a four-figure sum from both employers after he was exposed to noise when using pneumatic drills and other power tools. He two took legal action against Sheffield Council for failing to provide him with hearing protection while he worked for it between 1963 and 1969. Mr Fox was also exposed to excessive levels of noise while working on the construction of the Hallamshire Hospital for Henry Hargreaves & Sons Ltd from 1974 to 1977. He has now been left with a permanent hearing loss and has had to buy hearing aids as he struggles to hear conversations and high-pitched sounds such as birdsong. Mr Fox said: "Both jobs involved digging and construction work so I was working with loud machinery such as pneumatic drills and JCB diggers. My loss of hearing means that I now struggle to hear everyday conversations and it can be quite embarrassing when I have to ask people to repeat themselves several times." Law firm Irwin Mitchell secured the compensation from each employer in an out-of-court settlement. Nick Woods, industrial illness specialist at Irwin Mitchell, said: "We are pleased to have settled Mr Fox's case so he can access the help that he now needs. Noise-induced deafness can take a number of years to develop, and it's quite possible that a number of Mr Fox's colleagues, through no fault of their own, will have suffered similar injuries as a result of their exposure to noise. Employers must understand the need to provide the correct equipment and protection to their employees, as Mr Fox's injuries would have easily been avoided with basic hearing protection."