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On-road and wind-tunnel measurement of motorcycle helmet noise

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The noise source mechanisms involved in motorcycling include various aerodynamic sources and engine noise. The problem of noise source identification requires extensive data acquisition of a type and level that have not previously been applied. Data acquisition on track and on road are problematic due to rider safety constraints and the portability of appropriate instrumentation. One way to address this problem is the use of data from wind tunnel tests. The validity of these measurements for noise source identification must first be demonstrated. In order to achieve this extensive wind tunnel tests have been conducted and compared with the results from on-track measurements. Sound pressure levels as a function of speed were compared between on track and wind tunnel tests and were found to be comparable. Spectral conditioning techniques were applied to separate engine and wind tunnel noise from aerodynamic noise and showed that the aerodynamic components were equivalent in both cases. The spectral conditioning of on-track data showed that the contribution of engine noise to the overall noise is a function of speed and is more significant than had previously been thought. These procedures form a basis for accurate experimental measurements of motorcycle noise. © *2013 Acoustical Society of America*. [http://dx.doi.org/10.1121/1.4817913]

I. INTRODUCTION

Noise-induced hearing loss in motorcyclists is a problem which is known to affect professional riders,[1] in particular police officers[2,3] and racing riders.[4] Previous studies of the causes and extent of such hearing damage have largely been motivated by the health and safety implications of hearing impairment and the resulting potential for litigation.

In the late 1980s it was reported[5] that noise levels at the ear of a rider can exceed 90 dBA at a speed of 50 km/h (30 mph) and can reach 105 dBA at a speed of 112 km/h (70 mph). Given such high noise exposures, it is no surprise that professional riders have been found to have hearing loss ranging from 6% in driving instructors to 40% in racing riders,[1] where hearing loss is the percentage of the exposed population that will suffer a reduction in hearing sensitivity of 30 dB or more.

While there have been a number of studies which have measured the noise inside a helmet there is a wide discrepancy in their findings where differences of up to 15 dBA can be reported for the same driving speed.[1,5,6] Few researchers have studied how the interaction between the numerous noise sources, such as the engine, windscreen, and flow around the helmet, combine to generate the at-ear sound. The work reported here is a first step toward a more detailed examination of the nature and mechanisms of noise generation and transmission in helmets.

II. EXPERIMENTAL FACILITIES AND INSTRUMENTATION

The helmet used in the laboratory experiments was taken from a series of helmets provided by manufacturers for noise investigations. As such, the make and model is covered by a confidentiality agreement. It is a commercially available extra large (XL) motorcycle helmet the dimensions of which were approximately 26 cm × 25 cm × 36 cm.

The large wind tunnel facility at the University of Bath was used to test the motorcycle helmet in isolation. This closed loop facility has a 2 m × 1.5 m × 3 m test section and provides flow velocities up to 25 m/s with a free-stream turbulence intensity of 5%. The motorcycle helmet was mounted on a structurally isolated rig capable of controlling helmet angle relative to the free stream, referred to as the high alpha rig. This provided dynamic control of helmet position while isolating the helmet from any wind tunnel vibrations. The helmet was mounted on an expanded polystyrene mannequin head. Microphones were embedded within the head at ear and microphones were also mounted at the positions used on the human rider during the

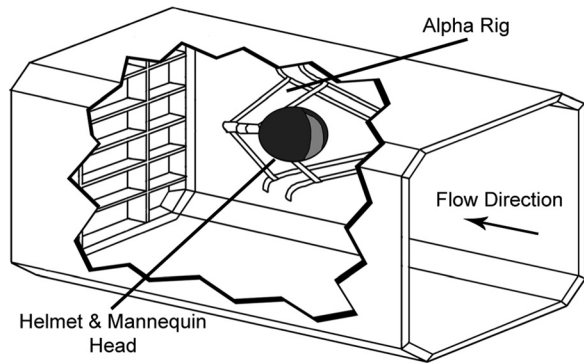a)Author to whom correspondence should be addressed. Electronic mail: kennedj@tcd.ie

FIG. 1. Large wind tunnel facility.

FIG. 3. Parameters of wind-tunnel windscreen rig: $L = 700\,mm$; $30° \leq \alpha \leq 90°$; $150\,mm \leq x \leq 850\,mm$; $-50\,mm \leq h \leq 150\,mm$.

on-track tests. Figure 1 shows the set-up within the wind tunnel.

Measurements were acquired using $\frac{1}{4}$ in. 130D20 PCB Piezotronics microphones connected to a PCB 442B117 signal conditioner. The microphone data were acquired using a 16 channel National Instruments DAQ system which consisted of a personal computer with a NI-PCI-MIO-16E-1 acquisition card and BNC-2090 connector box. The microphones were calibrated using a Larson Davis CAL200 calibration unit.

A set of full-scale tests were conducted at the Llandow Circuit, South Wales shown in Fig. 2. On a closed track it was possible to control speed and to have the rider filmed from an accompanying car, to record his riding position and head angle. The motorcycle used was a 2008 Suzuki GSXF-650 and the helmet a Shoei Raid II. An additional support vehicle, a Saab 9-5, was used to film the riding conditions by means of a camcorder mounted in the side window. Two GPS units were used to give reference data on motorcycle position and speed over the course of a test. The first unit was mounted on the motorcycle dashboard and used by the rider to maintain the test speed along the length of the straights. The second GPS unit inside the support vehicle was filmed in the same field of view as the rider to provide a record of test conditions.

Instrumentation consisted of a Linux based netbook with a USB-DUXfast 16 channel DAQ system, a purpose built connector box and mini-XLR Lavalier microphones. Because of the limitations of this system in acquiring long duration data sets additional measurements were acquired using an Edirol R-09 stereo digital recorder and miniature Knowles microphones. Both microphone systems were calibrated using a reference $\frac{1}{4}$ in. 130D20 PCB microphone
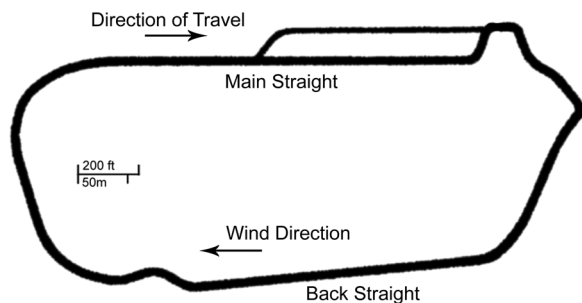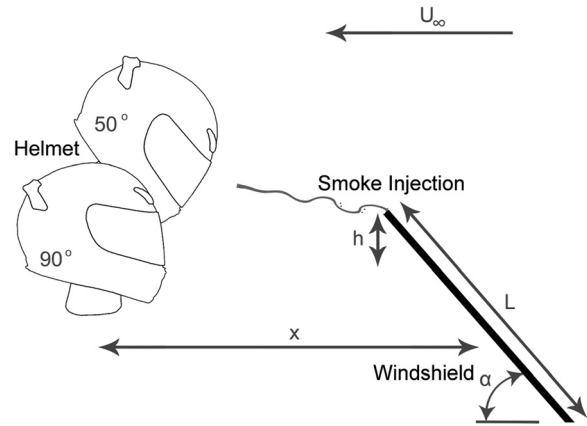

FIG. 2. Llandow circuit.

calibrated with the Larson Davis CAL200 unit. Additional tests were conducted in the wind tunnel using both of these acquisition systems.

The wind tunnel facility also features a custom built and removable windscreen rig. This rig consists of a flat 700 mm square plate which can be positioned over a range of distances and angles relative to the helmet, Fig. 3. The rig was used to recreate the windscreen conditions of the road bike as accurately as possible.

III. TRACK TESTS

Using the netbook-based acquisition system a series of tests were conducted on track at different speeds. Two microphones were used. The first was mounted at ear within the helmet while an external microphone was located just above the engine exhaust. Data were acquired by the netbook system with acquisition bursts of 10 s along the main straight of the test circuit. Data were acquired at test speeds of 40, 60, 80, and 100 km/h.

In order to provide further data on the effect of vehicle speed and rider position on sound pressure level and spectral content a second series of tests were conducted using the digital recorder. The motorcycle rider conducted a series of test laps at speeds of 40, 60, 80, 100, 120, and 140 km/h on the back and main straights of the track. The digital recorder continuously acquired data and the rider provided audio cues at the start of each straight. The wind speed on the test day was 4.6 m/s in line with the main straight and against the direction of travel along the main straight. This altered the effective air speed along the straights from the road speed measured by the GPS units.

A final series of tests was conducted at a speed of 80 km/h to investigate the effects of riding position and visor condition. Three riding positions of fully upright, half forward, and fully forward were used and recorded by the support vehicle. In addition a test was conducted where the helmet visor was partially open and the rider was fully upright.

IV. WIND TUNNEL TESTS

A series of tests were conducted in the large wind tunnel facility for comparison with the realistic driving data. An

initial test run was conducted to calculate sound pressure level as a function of speed for a raw comparison with track results. Flow speeds were recorded using a digital manometer and a hot wire and acoustic data acquired using the $\frac{1}{4}$ in. PCB microphones and National Instruments DAQ system.

At the available flow speeds tests were conducted at 40, 60, and 80 km/h using the same netbook based acquisition system as for the track tests. Microphones were placed at ear on the mannequin head and on the tunnel wall.

A final series of tests were conducted using the $\frac{1}{4}$ in. PCB microphones and the windscreen rig in the configuration most similar to the road motorcycle windscreen.

V. SPECTRAL CONDITIONING TECHNIQUES

The wind tunnel used has no acoustic treatment and as such there is a risk of signal contamination by background noise. The at-ear noise measured inside a helmet in isolation is driven by the flow interactions on the helmet surface. The contributions from wind tunnel noise will be significantly attenuated when passing through the helmet structures and will therefore be mainly transmitted through air paths. The contamination of the at-ear signals will be much less severe than for the case of microphones in the wind tunnel flow and can be accounted for by the application of a signal conditioning technique. In order to extract a "helmet-only" spectrum, containing only the noise due to flow over the helmet, we apply a signal conditioning procedure which has been used in a number of applications[7,8] to conditionally remove unwanted contributions to the output signal, in this case the contribution of the wind tunnel noise to the at-ear spectra.

Also, we wish to compare wind tunnel measurements to data taken on a motorcycle where there is a contribution to the in-helmet noise from the motorcycle engine and from environmental sources. During the on-track test an engine exhaust microphone was used to acquire data on these noise sources. The same spectral conditioning technique can be used here to separate the at-ear noise spectra into parts which are correlated and uncorrelated with the engine microphone. The correlated component represents the part of the engine noise which has been transmitted to the at-ear microphone. In this case the uncorrelated component will be dominated by the "helmet-only" noise sources.

A model for the system is shown in Fig. 4. The output signal $p(t)$ is composed of a sum of inputs $g_i(t)$, $i = 1, 2, \ldots$, each of which passes through a linear operator L_i. Passage
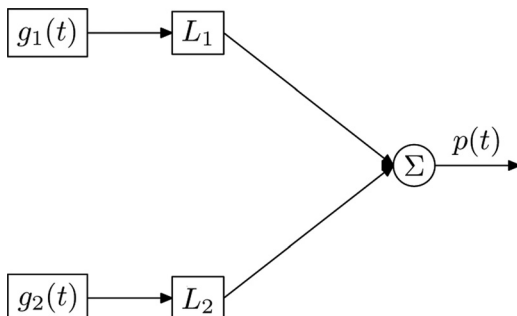
through a linear operator has no effect on the correlations on which the method depends. If we consider a two input problem, where $g_1(t)$ is a background noise contribution to $p(t)$ and $g_2(t)$ is the "real" aerodynamically generated noise in the helmet, we wish to remove from $p(t)$ the part of the signal which is correlated with $g_1(t)$. This is readily done using standard signal processing methods.

The method of partial coherence is a systematic technique for performing this decorrelation in order to rigorously assess the contribution of different sources. If the inputs are uncorrelated, the coherence function of each with the output signal is

$$\gamma_{ip}^2(f) = \frac{|G_{ip}(f)|^2}{G_{ii}(f)G_{pp}(f)},$$

where $G_{pp}(f)$ is the autospectrum of $p(t)$, $G_{ii}(f)$ is the autospectrum of $g_i(t)$ and G_{ip} is the corresponding cross-spectrum. The contribution of the ith source to the output can then be removed by subtracting the correlated part

$$G_{pp.i} = (1 - \gamma_{ip}^2)G_{pp}. \tag{1}$$

The notation $G_{pp.i}$ denotes the spectrum of the signal $p(t)$ with the contribution of the ith input removed.

As detailed in previous work by the authors[9] this technique can be expanded to remove multiple correlated sources from the system output. To return to the concrete example, if the output signal is an at-ear noise recording and inputs 1 and 2 are measures of background noise, $G_{pp.2!}$ is the spectrum of the at-ear noise with the background noise removed, in other words, an estimate of the "true" aerodynamic noise.

VI. RESULTS

Identical data acquisition and spectral analysis conditions were used during both the on-track and wind-tunnel measurements. The data were sampled at 44.1 kHz and the spectra were calculated using a block length of 2048 points. During the measurements at higher speeds on-track it was not possible to acquire more than 1.5 s of continuous data at the test speed. This set a limit on the number of averages

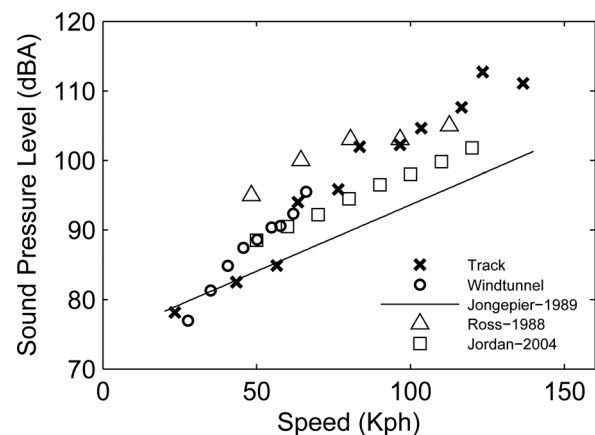FIG. 4. System model for partial coherence processing.

FIG. 5. Sound pressure level vs speed for conducted on-track and wind-tunnel measurements compared with literature (Refs. 1, 5, and 6).
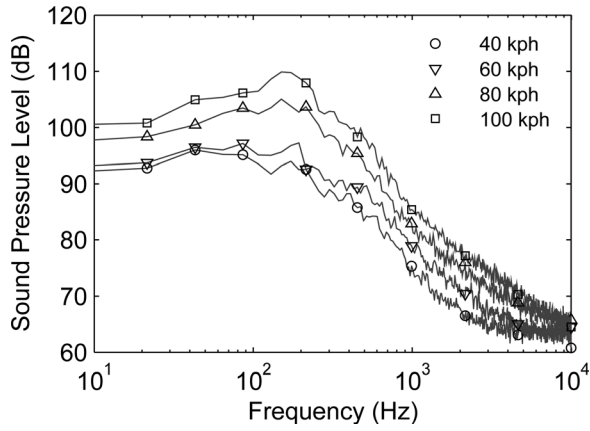
FIG. 6. Spectral shape vs speed.

that could be used when calculating the spectra which was then applied to all other measurements. All of the reported spectra were calculated using 80 averages with a 75% overlap on the block length of 2048 points.

The spectra reported in this work have not had A-weighting or similar filtering applied to the data. The close contact of the motorcycle helmet to the rider's skull is likely to produce body and bone conducted sound
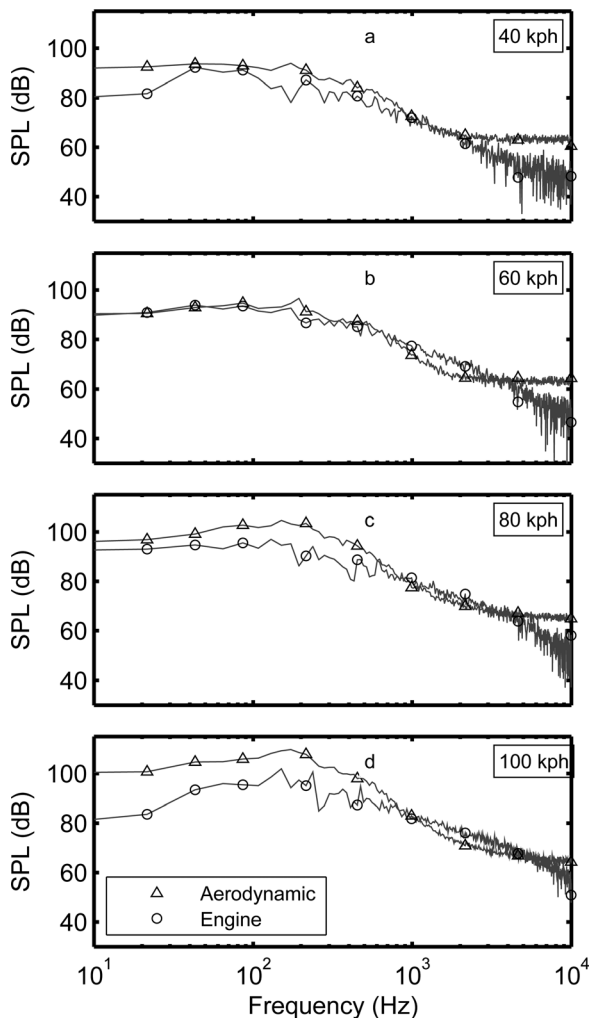

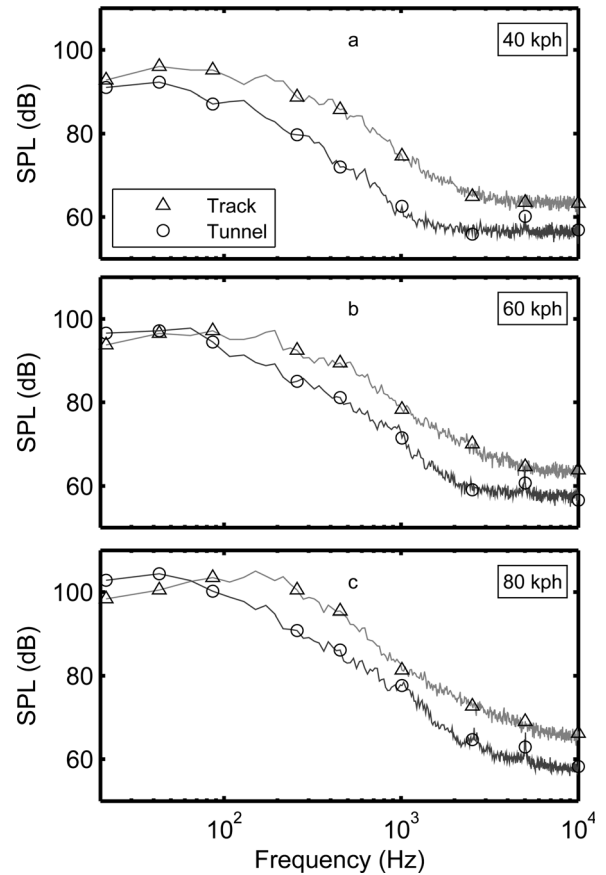FIG. 8. Track and wind tunnel at-ear spectra.
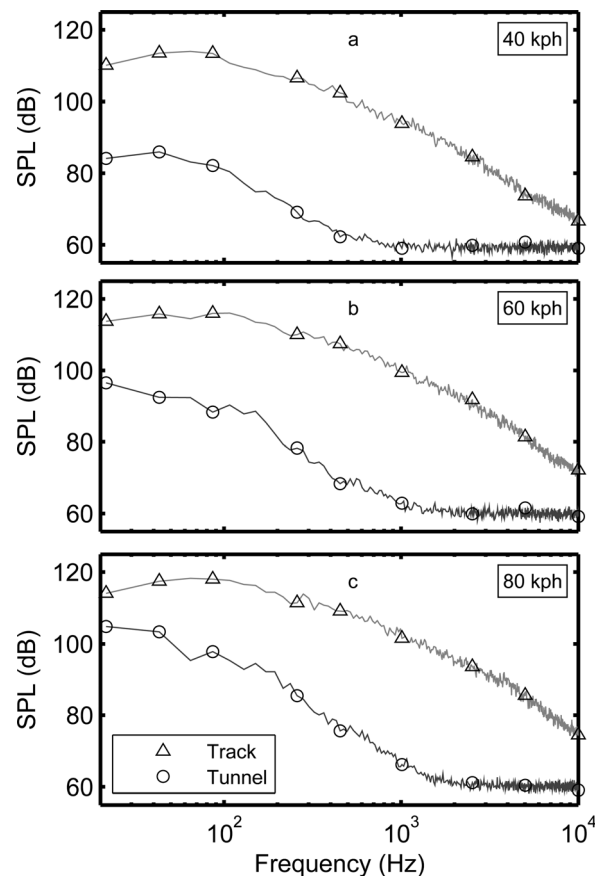

FIG. 7. Aerodynamic and engine components of at-ear spectra.

FIG. 9. Track engine and wind tunnel background spectra.
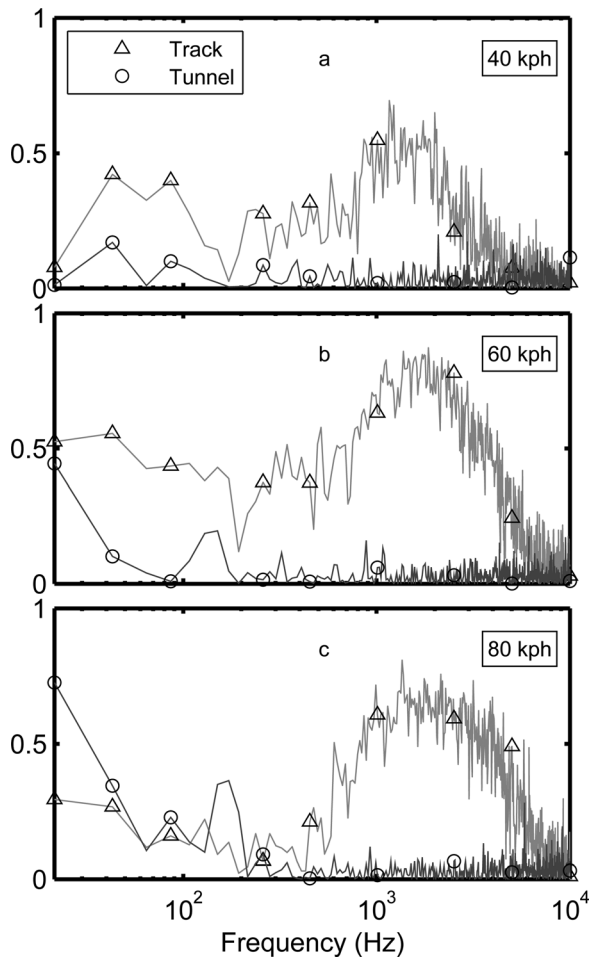
FIG. 10. Coherence functions for track and wind tunnel experiments.

FIG. 11. Aerodynamic components of track and wind tunnel at-ear spectra.

these noise sources to the at-ear spectra is revealed by the coherence function plots shown in Fig. 10. The same signal processing technique was then conducted to remove the engine and tunnel noise components from the at-ear data.

The resulting aerodynamic components are compared in Fig. 11. The wind-tunnel measurements were conducted at flow velocities based on the vehicle test speeds without

transmission that can not be measured by a microphone at the entrance to the ear canal. In this case A-weighting may not truly reflect the sound levels experienced by the rider and the spectra have therefore not been filtered.

Figure 5 shows the results for sound pressure level as a function of speed for the wind tunnel and track tests, with the on-track speeds adjusted for relative wind speed. Data are also shown from previous studies[1,5,6] where equivalent tests have been conducted. The recorded sound pressure levels were A-weighted to allow a comparison with the results from the literature.

Data from the track tests were used to investigate the change in spectral shape of the noise as a function of speed. Figure 6 shows the at-ear spectra calculated for each of the speeds used during the track test.

Using the techniques outlined in Sec. V the engine microphone data were used to separate the at-ear data into engine and aerodynamic components, shown in Fig. 7. For this purpose it is assumed that all noise not correlated with the engine is produced through an aerodynamic process.

Figure 8 shows the uncorrected at-ear microphone spectra from both the on-track and wind tunnel test campaigns as a function of speed. These spectra are contaminated by noise from the engine and wind tunnel background noise. Figure 9 shows the spectra of the engine and wind tunnel background microphones as a function of test speed. The contribution of
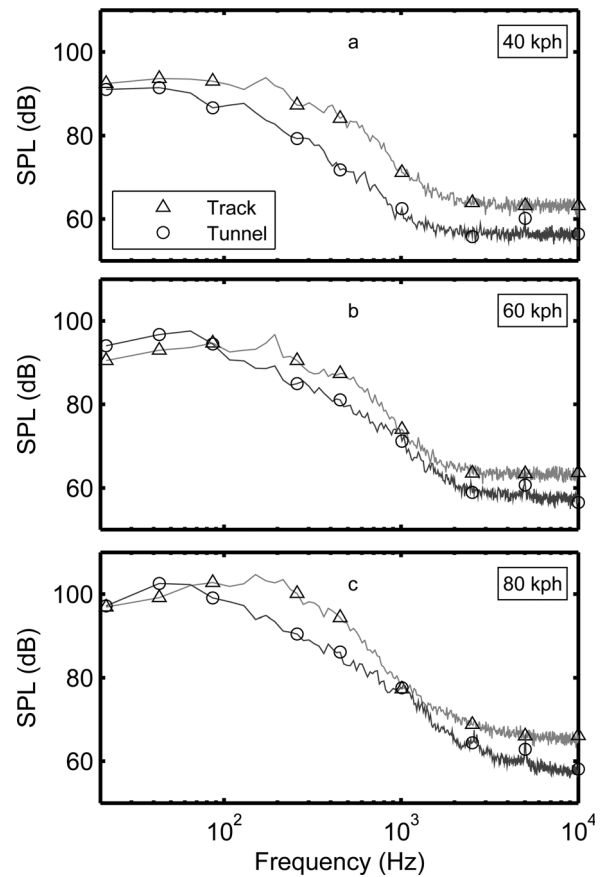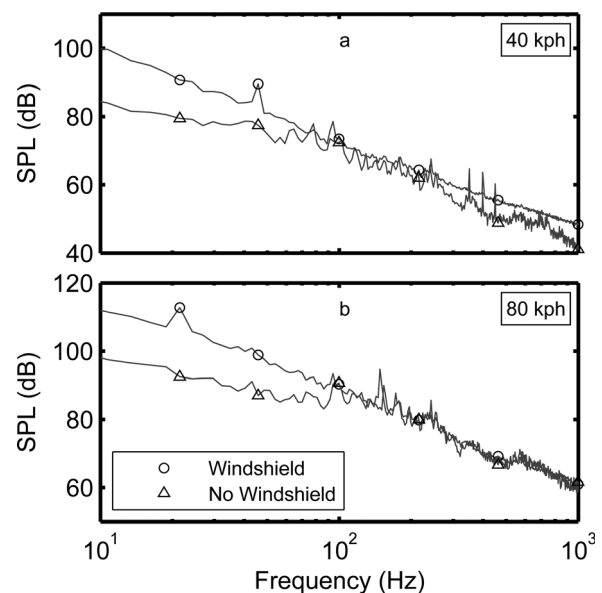

FIG. 12. Windscreen vs no windscreen at-ear spectra.

consideration of the effects of wind-speed. This puts the flow velocity within the wind-tunnel between the relative flow velocities experienced by the rider on the main and back straights of the test track.

Further tests were conducted in the wind tunnel investigating the effect of the windscreen on the at-ear sound. The resulting change in spectral shape is shown in Fig. 12. The location of the windscreen tip and the angle of the plate relative to the helmet are equivalent to the on-track test case. These data were acquired using the $\frac{1}{4}$ in. PCB microphones and National Instruments DAQ system.

VII. DISCUSSION

There exists a wide discrepancy in the reported literature on how sound pressure level varies as a function of speed while motorcycling. As can be seen in Fig. 5 the level reported by existing literature varies by over 15 dBA for a given test speed. It is interesting to note that the results from the track test carried out during this investigation closely follow each of the previously reported data sets for different speed ranges. There are a number of possible explanations for this. First, the sound experienced at ear is a superposition of numerous noise sources and the relative importance of these sources may vary differently both as a function of speed and other variables such as motorcycle geometry or engine type. Second, there are environmental factors such as contamination from other traffic and varying wind speeds. On the day of the track tests reported here, there was an average local wind speed of 4.6 m/s in the direction of the main straight. While GPS units were used by the rider to ensure a constant speed along the test straights the effect of the wind was to introduce an effective difference of 16.5 km/h between the back and main straight. If this is not factored into the calculations it results in a 5 to 10 dBA difference between the recorded sound pressure levels at an identical road speed.

Also shown in Fig. 5 are the results of an initial wind tunnel measurement of sound pressure level as a function of flow speed. In this case it is possible to control the flow velocity precisely however the results are contaminated by the presence of background noise from the wind tunnel. In addition to this the wind tunnel test lacks the contribution to the noise of the engine and additional aerodynamic sources such as the windscreen and rider body. Despite this the recorded sound pressure level (SPL) is roughly equivalent to the previously reported data above 50 km/h.

Spectral analysis of the data was conducted to investigate the effect of speed on the frequency content of the at-ear sound. Figure 6 shows a variation in spectral shape as speed is increased from 40 to 100 km/h during the on-track tests. This may be an indication that the contribution of different noise sources to the overall sound changes as a function of speed. In order to investigate this hypothesis the contribution of the engine noise was separated from the at-ear spectra. Since the tests were conducted on an isolated track the remaining sound was considered to be produced by aerodynamic sources relating to the helmet.

Figures 7(a)–7(d) show how the contribution of engine noise changes as a function of speed. At 40 km/h the aerodynamic component is more dominant for frequencies below 1 kHz where the majority of the sound energy lies. The situation at 60 km/h is quite different as the engine and aerodynamic sources are equivalent below 1 kHz and the engine is more dominant between 1 and 3 kHz. As speed increases to 80 and 100 km/h the aerodynamic component again dominates below 1 kHz but the engine is still the main contributor to sound in the 1 to 3 kHz range. The changing contribution of the engine goes some way to explaining the change in spectral shape as a function of speed.

By applying the same signal processing technique to remove the background noise from the wind tunnel tests the aerodynamic components of the at-ear sound could be compared with the track results. The coherence plots shown in Fig. 10 demonstrate that the contamination of the at-ear spectra by these non-aerodynamic noise sources is a function of speed. The wind tunnel contamination is at low frequencies generally below 100 Hz and is minimal at the lowest test speed. The track test microphone will contain contributions primarily from the engine but also from other sources such as tire noise due to the location of the microphone at the engine exhaust above the rear tire. Following the application of the signal conditioning the results for speeds of 40, 60, and 80 km/h are shown in Figs. 11(a)–11(c).

While it is impossible to precisely match the speeds, and hence the sound pressure levels between track and tunnel test due to the effects of wind speed, of relevance here is the change in spectral shape as a function of speed. The spectral shape of the aerodynamic component of the at-ear sound is not the same in the track case as in the case of an isolated helmet in the wind tunnel. While there is a similar spectral shape found at 40 km/h the differences become more prominent as speed increases. There is a clear hump visible between 100 and 1000 Hz in the 60 and 80 km/h spectra from the track.

While the spectra in Figs. 11(a)–11(c) represent the aerodynamic components of the at-ear sound for both tests, it is possible that not all of the aerodynamic sources are contained in the wind tunnel measurement, for an isolated helmet. The windscreen was identified as a potentially significant source of additional aerodynamic noise not found in the wind tunnel tests. The custom windscreen rig, built for a separate investigation by the authors,[10] was used to recreate the road motorcycle windscreen within the wind tunnel. A series of measurements of at-ear sound pressure level using the $\frac{1}{4}$ in. PCB microphones and National Instruments DAQ system were then made.

Figures 12(a) and 12(b) show the effect of the windscreen on the spectral shape at 40 km/h and 80 km/h. The effect of adding the windscreen to the tunnel was to create a hump in the spectra below 100 Hz. While this is not in the same frequency range as the hump found in the on-track spectra it was found that the frequency range could be changed by altering the windscreen configuration in the wind tunnel.

A significant difference exists in the flow conditions between the wind tunnel, which has been treated for a low turbulence intensity, and the atmospheric flow conditions experienced during the on-track measurements. This may

TABLE I. Effect of riding position on SPL.

Riding position	SPL (dB)
Fully upright	103
Half forward	113
Fully forward	113
Fully upright (visor partially open)	106

also be a factor in determining the frequency range which contains the effect of the windscreen. The importance of the interaction of the windscreen flow with the helmet during the on-track measurements is highlighted by Table I which shows the result of a change in rider position at a constant speed on the track.

The difference between the fully upright and half forward riding positions results in a change of 10 dB in the at-ear noise levels. These positions are both valid for riding the motorcycle in question and the difference is one of personal choice and driving style. This increase in noise level can best be explained by a change in the interaction of the rider with the windscreen flow.

VIII. CONCLUSIONS

This investigation has gone some way to addressing the problems of measuring the exposure of motorcycle riders to noise.

The discrepancies that exist between previous measurements of noise exposure may potentially be explained by external factors such as the importance of wind speed during on-road or on-track tests.

The spectral conditioning technique used in this work has proven to be an insightful tool for investigating the contribution of individual noise sources to the at-ear sound. Three main contributors to the at-ear sound spectra have been identified, namely, the engine, the windscreen and the helmet.

While it is possible that the aerodynamic noise produced by the helmet increases as a simple function of flow speed the contributions of the engine and windscreen have been shown to be more complex. The engine was a stronger contributor to the at-ear spectra than the aerodynamic noise between 1 and 3 kHz even at high speeds of 100 km/h. The increasing contribution of the windscreen to the at-ear noise was highlighted by the increasing divergence of the track

and wind tunnel aerodynamic spectra at higher speeds and by the change in SPL experienced by the rider for different riding positions during the on-track tests.

The question of whether it is possible to produce identical aerodynamic noise spectra in the wind tunnel and on the road is still open. The spectral conditioning technique used in this work has proven to be a valuable tool in identifying differences between the test conditions and assessing the contribution of various noise sources. The development of a satisfactory wind-tunnel setup for the measurement of noise in motorcycle helmets is still ongoing and this work has highlighted the importance of windscreen flow interactions in assessing the overall noise levels.

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