

# A method of predicting variable speed rail corrugation growth using standard statistical moments

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## ABSTRACT

Wear-type rail corrugation is a significant problem in the railway transport industry. Some recent work has suggested that speed control can be used as an effective tool to minimize the rate of corrugation growth. This has brought about the need to model corrugation growth under variable passing speed. Variable speed rail corrugation growth modelling normally consists of either numerical simulation of a sequence of varied speed wheel passes or direct integration of a probabilistic passing speed distribution function; both of which are computationally expensive. This paper investigates the use of the statistical moments of the speed probability density function to greatly improve the computational speed of variable speed corrugation growth models and compares results of changing standard deviation and skewness to numerical integration models. It also identifies the effects of individual statistical moments on corrugation growth to provide better insight into control methods. The new modelling method correlated well with the numerical integration models for small standard deviations in speed (less than 10%) and highlighted a need to consider kurtosis in predicting the performance of speed control based corrugation mitigation schemes. For larger standard deviations in speed, higher than 4th order effects need to be considered.

## INTRODUCTION

Wear-type rail corrugation is a periodic wear pattern that develops on running rail heads with extended use. It has a characteristic wavelength of 25-400 mm and occurs in rail networks worldwide (Sato et. al., 2002). This surface irregularity grows as a function of train passages causing serious unwanted noise and vibration (see Hempelmann and Knothe, 1996). Figure 1 shows a corrugation profile after approximately 9 months of passenger rail traffic.



Figure 1 - 9-month-old corrugated rail profile

Fully developed corrugation on rails causes excessive noise and vibrations of the vehicle and track, inevitably leading to expensive reprofiling of the rail by grinding. This process is currently costing the Australian rail industry in excess of AU\$ 10 million every year and it will cost more with predicted increases in rail traffic density unless alternative mitigation methods are put in place. Recent studies on rail corrugation have suggested that uniformity in train passing speed accelerates the growth of corrugations and that speed control offers a possible practical solution to controlling growth rate (see Bellette et. al., 2008 and Meehan et.al.,2009). Preliminary field testing has provided ranges of expected statistical spreads in speed which require accurate and efficient modelling to make predictions of changes in corrugation growth rate.

Analytical frequency domain corrugation prediction models have shown the capacity to predict dominant frequencies and amplitude growth rates of rail corrugation (see Hempelmann and Knothe, 1996, Müller, 2001, Wu and Thompson, 2005, Grassie and Johnson, 1985, Tassilly and Vincent, 1991 and Batten et. al., 2011). More complex three dimensional numerical models are computationally expensive, making effective analysis of speed distribution effects over many vehicle passes difficult.

Currently, variable speed corrugation growth modelling methods consist of either, A: direct integration of an assumed speed distribution function (Bellette et. al., 2008, Batten et. al., 2010) or B: simulation of multiple single wheel or bogie passes to find an equivalent distributed speed growth rate (Meehan et. al., 2009). Method A has also been used to model growth of corrugation on road surfaces under stochastically varying speed in Hoffmann and Misol (2008). Machine tool chatter has also been modelled with speed variance effects, showing that speed variation may increase the area of regions in parameter space where chatter does not occur. However, such chatter models only model a deterministic speed sequence, not probabilistic (see Namachchivaya and Beddini, 2003). That is, the speed is a chosen function of time, making analysis simpler but not appropriate for corrugation growth modelling as tracking a predefined speed sequence with a high enough accuracy is unrealistic in practice.

Of the two previously developed methods, integration of a speed distribution function (A) provides much more accurate predictions of growth rate but requires significant computational complexity to accurately integrate the distribution curve numerically. Simulation of successive wheelset passages (B) removes the need for numerical integration but accurate representation of a known speed distribution requires many simulated passes, also increasing the computational expense.

This paper aims to present a new method of modelling variable speed corrugation growth, based on the truncated series expansion of the expectation of the frequency domain corrugation growth spectrum in terms of the moments of the speed

probability density function. Results are benchmarked against the model presented in Meehan et. al. (2009) using Gaussian distributions of speed to analyse standard deviation and triangular distributions to analyse standard skewness like those in Batten et. al., (2011). An investigation was also performed using this new modelling technique to predict and provide insight into the effects of higher order statistical speed moments (such as kurtosis) on corrugation growth.

**MODELLING**

The following subsections demonstrate, firstly, how an existing variable speed corrugation growth model is used to investigate standard deviation and standard skewness effects on rail corrugation growth on straight track and, secondly, how the same results can be produced using a simpler linearised model based on standard statistical moments instead of integrating a variable passing speed probability density function.

**Probabilistic speed corrugation growth on straight track**

The single pass corrugation growth model used in this paper is based on that presented in Meehan et. al., (2009). A single mode approximation is made of a field-measured corrugation growth spectral density plot and the parameters used to calculate the effects of a distributed passing speed. The full equation for single-mode dominant corrugation growth rate spectrum,  $G_r$ , under a distributed passing speed function,  $p(x)$ , is given below, where  $K_b$  is the sensitivity of wear depth to dynamic normal force,  $\omega_n$  is the natural frequency,  $\zeta$  is the damping ratio and  $K_c$  represents the modal sensitivity of the wheel/rail displacement to a change in longitudinal rail profile (all given in Appendix A).

$$G_r(\omega) = \left| \frac{Z_{n+1}}{Z_n} \right| - 1 = \exp \left( \int_{-\infty}^{\infty} \ln f(x, \omega) p(x) dx \right) - 1 \tag{1}$$

where,

$$f(x, \omega) = \ln \left( \frac{(\omega_n^2 (1 - K_b K_c / (1 + K_b)) - x^2 \omega^2)^2 + (2\zeta \omega_n x \omega)^2}{(\omega_n^2 - x^2 \omega^2)^2 + (2\zeta \omega_n x \omega)^2} \right) \tag{2}$$

Two different speed distribution shapes were used to observe the effect of altering standard deviation and standard skewness in speed distribution on corrugation growth rate under fixed kurtosis. For the purpose of analysing standard deviation effects, both Gaussian and triangular distributions with 4 standard deviations were integrated using equation (1). The triangular distributions were also used with a series of 5 standard skewnesses to show the effects of speed distribution asymmetry. Appendix B provides the equations and input parameters used for the Gaussian and triangular speed distributions.

**Statistical moment variable speed corrugation growth**

The objective here was to use a Taylor approximation of the logarithm growth expression to obtain a simpler and more tangible expression in terms of the statistical moments of the speed distribution; average,  $\mu$ , standard deviation,  $\sigma$ , standard skewness,  $S$ , and kurtosis,  $k$ , in place of the integrated speed distribution function. By taking a third order Taylor expansion of equation (2) about the average speed,  $\mu$ , the following equation is produced.

$$f(x, \omega) \approx f(\mu, \omega) + \frac{df(\mu, \omega)}{dx} (x - \mu) + \frac{d^2 f(\mu, \omega)}{dx^2} \frac{(x - \mu)^2}{2} + \frac{d^3 f(\mu, \omega)}{dx^3} \frac{(x - \mu)^3}{6} + \frac{d^4 f(\mu, \omega)}{dx^4} \frac{(x - \mu)^4}{24} \tag{3}$$

When multiplied with the distribution function,  $p(x)$ , and integrated for the full domain of speeds as per equation (1), the first four statistical moments appear in the result.

$$\int_{-\infty}^{\infty} f(x, \omega) p(x) dx \approx f(\mu, \omega) + \frac{d^2 f(\mu, \omega)}{dx^2} \frac{\sigma^2}{2} + \frac{d^3 f(\mu, \omega)}{dx^3} \frac{S\sigma^3}{6} + \frac{d^4 f(\mu, \omega)}{dx^4} \frac{k\sigma^4}{24} \tag{4}$$

Where, the integral expressions for the first four statistical moments are as follows.

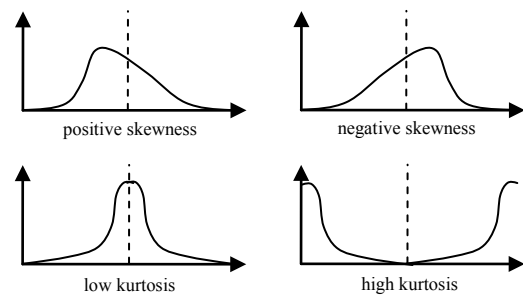
$$\mu = \int_{-\infty}^{\infty} x \cdot p(x) dx \tag{5}$$

$$\sigma^2 = \int_{-\infty}^{\infty} (x - \mu)^2 p(x) dx \tag{6}$$

$$S = \int_{-\infty}^{\infty} (x - \mu)^3 p(x) dx / \sigma^3 \tag{7}$$

$$k = \int_{-\infty}^{\infty} (x - \mu)^4 p(x) dx / \sigma^4 \tag{8}$$

The mean,  $\mu$ , defines the centroid of the area enclosed by the distribution function,  $p(x)$ . The variance, or standard deviation squared,  $\sigma^2$  measures the spread of the distribution about the mean. The skewness,  $S$ , defines the asymmetry about the mean and the kurtosis,  $k$ , compares the difference in density between the centralized coordinates (i.e. close to the mean) and the tail sections of the distribution shape. For clarity, the kurtosis and skewness effects on distribution shape are shown in Figure 2.



**Figure 2** – Effects of kurtosis and skewness on distribution shape

Equation (4) can be substituted back into equation (1) to obtain the variable speed growth rate in terms of the first three statistical moments instead of an integral of the distribution function.

$$G_r(\omega) \approx \exp \left( f(\mu, \omega) + \frac{d^2 f(\mu, \omega)}{dx^2} \frac{\sigma^2}{2} + \frac{d^3 f(\mu, \omega)}{dx^3} \frac{S\sigma^3}{6} + \frac{d^4 f(\mu, \omega)}{dx^4} \frac{k\sigma^4}{24} \right) - 1 \tag{9}$$

So the corrugation growth rate at a given frequency for an arbitrary speed distribution shape can be approximated based on standard statistical measures, the single pass growth rate at the average speed and the double, triple and quadruple derivatives of growth rate at the average speed. For a more complex single pass corrugation growth function of speed, finite difference approximations of the double and triple derivatives may be used but for this paper the analytical derivatives of the single mode approximation were used (see Appendix B for input parameters).

The analytical equations for the first to fourth derivatives were derived with the use of Matlab’s symbolic functions. These were adequate for representing a highly damped frequency spectrum of corrugation growth but lower damping ratios caused the Taylor approximation to break down at a much narrower band of speeds since higher order effects were much more significant. Finite difference approximations with large step sizes would be more effective at representing these functions at larger standard deviations of speed from the average but this technique wasn’t used in this paper.

The following subsections present the simulation results for both the numerically integrated distribution shapes and the equivalent statistical moment expansions.

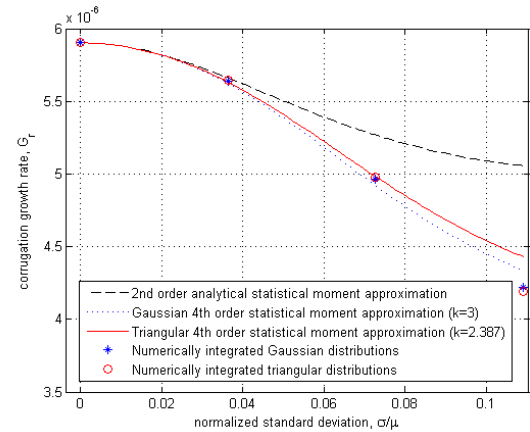
**RESULTS**

Equations (1) and (2) were solved numerically using the midpoint method for 500 equally spaced speeds and 100 equally spaced frequencies in Matlab using an Intel (R) Core 2 Duo 1.73 GHz CPU with 2 GB of RAM and a Windows XP Operating System. Both triangular and Gaussian distributions with an average speed of 55 km/h were solved for with a speed range of 16 times the standard deviation used in each case. Statistical moment results were obtained by solving Equation (9) for 100 frequencies with insertion of analytical solutions of derivatives provided by Matlab’s symbolic functions.

Firstly, the case of symmetric distributions of speed is investigated with both triangular and Gaussian distributions of zero skewness and varying standard deviation. 4 standard deviations were simulated and the results for the two modelling techniques compared. To test asymmetric cases, a series of 10 triangular distributions of two different standard deviations and 5 different skewnesses with equally spaced modes from  $\sigma\sqrt{2}$  to  $\sigma\sqrt{2}$  are then simulated.

**Standard deviation and kurtosis effects on growth rate**

To validate this modelling technique against predictions of increasing standard deviation on corrugation growth rate as per Meehan et. al. (2009), a series of Gaussian normal distributions and symmetric triangular distributions were integrated with the one mode single pass growth function as per equation (1) and the results of standard deviation against maximum corrugation growth rate (in frequency) were compared for the two modelling techniques. Second and third order Taylor expansions were used to observe the effect of the speed kurtosis on these predictions. The difference in the 2<sup>nd</sup> and 4<sup>th</sup> order approximations is directly related to the speed distribution kurtosis which provides insight into how kurtosis will affect corrugation growth rate. The results of these simulations are shown in Figure 3.



**Figure 3** – Gaussian and triangular distributions with varying standard deviation and their 2<sup>nd</sup> and 4<sup>th</sup> order statistical moment approximations

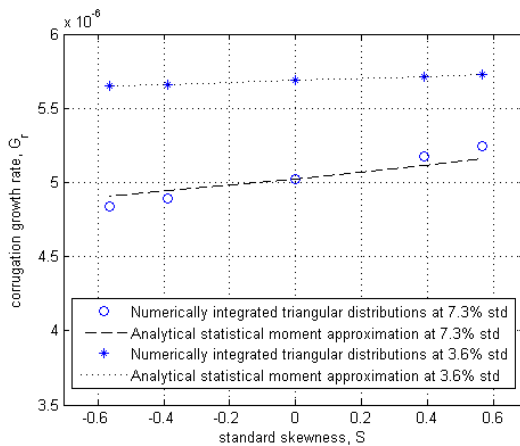
By inspection, as would be expected, the 4<sup>th</sup> order approximation matches closely to the numerically integrated solutions for narrower speed distributions but begins to diverge at higher standard deviations. By equation (9), the 4<sup>th</sup> term in the statistical moment expansion is proportional to the kurtosis and the standard deviation to the power of 4. This means that the difference between the 2<sup>nd</sup> and 4<sup>th</sup> order approximations of the Gaussian distribution is equal to the change in corrugation growth rate for an increase in kurtosis of 3. So by inspection of Figure 3, an increase in kurtosis of 3 equates to a decrease in corrugation growth rate of 17% from that achieved with a standard deviation of 11%.

Increasing the standard deviation from zero will always cause a reduction in corrugation growth rate at the dominant wavelength since the double derivative of growth rate with speed will always be negative here due to the nature of it being a local maximum. This is because, for any given wavelength of corrugation, there will be a critical speed at which corrugation growth will be promoted most. If the probability density at the critical speed for the dominant wavelength is reduced, without significantly altering that dominant wavelength, then there are less wheel passages close to resonant/critical conditions and hence corrugation growth will be reduced.

Kurtosis may cause an increase or decrease in corrugation growth rate, depending on the sign of the fourth derivative at the dominant wavelength as per Equation (9). At small standard deviations in speed the critical speed for corrugation growth at the dominant wavelength will be close to the mean so increasing kurtosis will reduce this probability density (see Figure 2) and subsequently reduce the corrugation growth at that wavelength. For larger standard deviations, however, the most critical speed for the dominant wavelength may be far enough away from the mean that increasing kurtosis will actually increase the probability density at that speed.

**Standard skewness effects on growth rate**

To validate the third order statistical moment approximations of skewness effects, five triangular distributions of varying skewness were integrated using equation (1) with a constant standard deviations of 7.3% and 3.6% and the same skewness values were used in a third order statistical moment approximation of each using equation 9. A constant was added to the statistical moment results representing higher than 4<sup>th</sup> order effects to account for the discrepancies seen in Figure 3 b) for the symmetric case. The results are shown below.



**Figure 4** – Skewness effects on corrugation growth rate from integrated triangular distributions and statistical moment expansion for standard deviations of 3.6% and 7.3%

Figure 4 shows the analytical statistical moment model matches the numerical results for small standard deviations (<10%). This indicates that higher than 3<sup>rd</sup> order statistical moment expansion is unnecessary for accurately predicting skewness effects on corrugation growth if the standard deviation is <10%. For larger standard deviations the approximation rapidly diverges from the solution obtained via integration. This indicates that the higher order effects which relate to speed distribution asymmetry, much like the third and fourth order terms in equation (9), are scaled with a factor of standard deviation.

Figure 3 also shows a slight increase in corrugation growth rate as skewness is increased. The reason that the trend in growth rate with skewness is opposite of that presented in Batten et. al. (2011) is that cornering effects are not considered and the single mode growth spectrum is dissimilar to 5 mode system presented previously.

Increasing or decreasing skewness will not always have the same effect on corrugation growth rate because it's dependent on the sign of the third derivative of growth rate with speed at the dominant wavelength. The results of these simulations and the results of the simulations performed in Batten et. al. (2011) show that the third derivative may be positive or negative, depending on site conditions. Under an increase in speed, the spectral density peaks will always widen in the spatial frequency domain as discussed in Batten et. al. (2011). If the frequency spectrum for a single pass is symmetric about its peak this will cause the third derivative of growth rate with speed at the dominant frequency to be negative. If there is a large enough reduction in slope magnitude in the wavelength domain comparing either side of the peak in growth rate then this effect may be countered, causing the third derivative at the dominant wavelength to be positive as was the case in this paper. Under cornering on under-canted track though, increasing skewness (i.e. biasing lower speeds) will most likely decrease corrugation growth rate since under-canted cornering conditions cause large increases in corrugation growth rate at higher speeds, much larger than the changes in growth rate presented here (see Batten et. al., 2011).

## DISCUSSION OF RESULTS

The new model was able to produce results much quicker than the integration and multiple pass models. Using an Intel (R) Core 2 Duo 1.73 GHz CPU with 2 GB of RAM running a Windows XP Operating System it took 77.9 s to solve one corrugation growth rate via integration of a Gaussian distribution as compared to 0.012s for the analytical approximation of equation (9). This is a significant saving in computational expense of almost 4 orders of magnitude ( $10^4$ ). For standard deviations of less than 10% the 4<sup>th</sup> order statistical moment approximations closely matched the numerically integrated results for symmetric Gaussian and triangular distributions. For asymmetric triangular distributions, at standard deviations below 4% the 3<sup>rd</sup> order statistical moment approximation was accurate in determining changes in corrugation growth rate with standard skewness.

As can be seen when comparing the two sets of integrated distributions, the kurtosis effect is minimal between the Gaussian and triangular distributions. The question must then be raised: can kurtosis change enough to significantly alter predicted results of increasing speed standard deviation? As part of a project undertaking field experiments to validate modelling predictions of corrugation growth under varying train speed (see Meehan et. al., 2009 and Batten et. al., 2010), a speed control system was installed on a site with a tight radius corner in suburban Brisbane that is known to rapidly corrugate on the low rail. Standard statistical measurements were taken before and after implementation of the speed control system which was designed to make the trains follow a new distribution having increased variance. The kurtosis decreased by 4.8 which is more than the difference between the 2<sup>nd</sup> and 4<sup>th</sup> order moment approximations. These approximations showed a factor of 1.8 difference in the effectiveness of widening passing speed when kurtosis was included. This means that for any speed control based corrugation mitigation system, the kurtosis change can be significant in predicting the effectiveness in reducing corrugation growth rate.

For every extra term considered in the truncated Taylor series expansion of equation (2) one extra statistical moment appears in the final growth rate equation. Every successive term included will have a diminishing effect on the corrugation growth rate function and will be scaled by a function of the first statistical moment, standard deviation. The trend in corrugation growth rate change for altering each statistical moment will be dependent upon the sign of its equivalent derivative from the single pass growth function, equation (2). The only universal effect will be that increasing standard deviation will decrease the corrugation growth rate at the dominant wavelength since the double derivative of corrugation growth at the dominant frequency will always be negative. Odd numbered terms represent effects relating to speed distribution asymmetry so these terms will equate to zero for a symmetric distributions of speed.

## CONCLUSIONS

This report presents a method by which variable speed corrugation growth can be rapidly approximated without the computational burden of numerical integration of a speed distribution function or simulation of many passes. Analytical equations were used to find the first four derivatives of growth rate in the frequency domain with train speed. These were used with standard statistical moments of standard deviation, skewness and kurtosis and the results compared with

numerically integrated triangular and Gaussian speed distribution functions. Results showed a good correlation between the 4<sup>th</sup> order statistical moments for the increased standard deviation simulations up to a standard deviation of 10% and between the 3<sup>rd</sup> order statistical moments and the varying skewness simulations when the standard deviation was small (less than 4% of the mean). Higher than 4<sup>th</sup> order statistical moments are expected to have increasing effect with larger standard deviations since the 4<sup>th</sup> order approximations matched closely with numerical solutions of standard deviation changes. Also, 3<sup>rd</sup> order approximations matched closely with results of skewness changes if the standard deviation was small but diverged rapidly as standard deviation was increased.

It was also shown how kurtosis can have significant effects on the performance of a speed control based corrugation mitigation scheme. Comparing the triangular and Gaussian distribution, results showed little difference but the 2<sup>nd</sup> and 4<sup>th</sup> order statistical moment results show a difference in predicted growth rate of 12% from that of the single pass growth rate. These correlated to a change in kurtosis of 3. The change in growth rate (17%) is significant when compared to the 27% caused by increasing the standard deviation to 11%. These effects will always depend on the 4<sup>th</sup> derivative of the growth rate function with speed so it is possible that under some conditions this trend will be reversed, as with those observed for skewness changes. Under cornering conditions though, the third derivative will normally be negative because of significant increases in wear sensitivity to normal force with higher speeds so reduction in skewness will cause a decrease in corrugation growth rate (see Batten et. al., 2011). The only universal effect will be that increasing standard deviation will always decrease corrugation growth at the dominant wavelength.

This paper shows that the method of modelling variable speed rail corrugation growth via statistical moment expansion will work for narrow speed distributions. As standard deviation increases however, higher order effects become more apparent and must be considered. Future work will consider the possibility of using a widely spread finite difference approximation to find the derivatives of growth rate with speed so as to improve lower order approximations at large standard deviations at the cost of diminished accuracy for small standard deviations.

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**APPENDICES**

**Appendix A – Simulation parameters**

Parameter	Symbol	Value
Natural frequency [rad/s]	$\omega_n$	850
Wear sensitivity [m/N]	$K_b$	$2.4 \times 10^{-6}$
Modal sensitivity	$K_c$	0.785
Damping ratio	$Z$	0.14
Average speed [m/s]	$\mu$	15.3
Kurtosis of distribution, Gaussian, triangular	$K$	3, 2.387

**Appendix B – Speed distribution functions**

The Gaussian distribution function is given by the following equation.

$$p(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}} \tag{B.1}$$

The triangular distribution must have a predefined mode,  $x_m$  which ranges from the root of two times the standard deviation either side of the defined mean.

$$x_{\min, \max} = \mu \pm \sigma\sqrt{2} \quad (\text{B.2})$$

Based on this mode, the upper and lower limits of speed can be calculated.

$$x_{\min, \max} = \frac{3\mu - x_m \pm \sqrt{-3x_m^2 + 6\mu x_m - 3\mu^2 + 24\sigma^2}}{2} \quad (\text{B.3})$$

With the domain limits and speed mode set, the distribution function,  $p(x)$ , is then bound by the following equations.

$$p(x) = \frac{2(x - x_{\min})}{(x_{\max} - x_{\min})(x_m - x_{\min})} \quad \text{If } x < x_m \quad (\text{B.4})$$

$$p(x) = \frac{-2(x - x_{\max})}{(x_{\max} - x_{\min})(x_{\max} - x_m)} \quad \text{If } x > x_m \quad (\text{B.5})$$



Front

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*Back and  
sides*

# Proceedings of Acoustics 2011: Breaking New Ground

2-4 November 2011  
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## *Preface*

Welcome to the Proceedings of ACOUSTICS 2011. This volume contains papers presented at the 2011 Annual Conference of the Australian Acoustical Society that was held on the Gold Coast in November 2011. The annual conference of the Australian Acoustical Society has a long history and has developed as an important forum for the dissemination of information relating to the science and practice of acoustics in Australia.

The theme for ACOUSTICS 2011 was *Breaking New Ground*. This theme was chosen to provide a focus for the Conference on the substantial infrastructure development projects currently being undertaken and being planned in the Australasian region. Major infrastructure for transportation, industry and mining, present challenges in noise and vibration, whether these are in assessment, modelling or mitigation or in the need to provide appropriate legislative and regulatory frameworks. The Proceedings of ACOUSTICS 2011 do break new ground with papers reviewing recent developments and addressing the challenges and opportunities presented by the construction and operational phases of such infrastructure.

The response to the call for papers from the acoustical community was outstanding. 140 abstracts were submitted for inclusion in the technical program for the Conference. These abstracts covered a broad range of topics. The theme was well supported with papers proposed for noise associated with major infrastructure projects and construction in contexts ranging from urban through to mining projects. Many abstracts were also submitted in the other major topics for which papers were called for the conference, underwater acoustics / marine bioacoustics, railway noise and vibration and road transport. Other abstracts on more general noise and vibration were received. The abstract review committee reviewed the abstracts and authors of abstracts accepted for the conference were invited to submit full papers. The larger Technical Review Committee, which included over 50 acoustics academics and professionals, reviewed the full papers. Each paper was reviewed by two to three members of the committee. After the outcome of the reviewing process, the final technical program for the conference included 103 papers.

Five workshops were included in the technical program for the conference. These were on *Wheel Rail Noise Control, Building Design for Transportation Noise, Wind Turbines and Low Frequency Noise, Sleep Disturbance and Low-Noise Road Surfaces*. These workshops were organised to be run within the program for the conference. In addition, a Short Course entitled, "*Environmental Noise Assessment*" was held in conjunction with the conference.

The editors of these proceedings would like to thank all authors for their efforts in preparing of their papers. Thanks also go to the Scientific Review Committee for their assistance in reviewing the large number of papers. As these proceedings are being published prior to the Conference, we look forward to the exciting technical program to a successful ACOUSTICS 2011.

David Mee  
Ian Hillock

October 2011

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## Information for Higher Education Research Data Collection (HERDC)

The HERDC is the annual collection of statistics from Australian universities about research output and income. It is currently collected by the Department of Innovation, Industry, Science and Research.

The following information is provided for authors intending to claim their research publications as part of the HERDC.

Title of conference publication	Acoustics 2011: Breaking New Ground Proceedings of the Annual Conference of the Australian Acoustical Society
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### Proof of peer review

Each of the manuscripts accepted to 'Acoustics 2011: Breaking New Ground' was reviewed by at least two members of a scientific committee comprising 42 members. The names of referees were kept anonymous from the authors. The referees reviewed the papers to ensure they were of high standard for the conference, and provided written feedback on the quality of the manuscripts. Where doubt remained after this process, the papers were reviewed by the scientific committee chairman. The referee criteria included: technical content, originality, clarity, English expression, technical significance. Papers were matched where possible to referees in the same field with similar interests and area of expertise as the authors. Authors were advised to make all changes recommended by the reviewers, or provide the editor with a technical justification for not making particular changes. The responses from authors were then reviewed by the editor.

The organising committee wishes to thank the scientific committee and the authors for their cooperation and time to enable this review process to occur.

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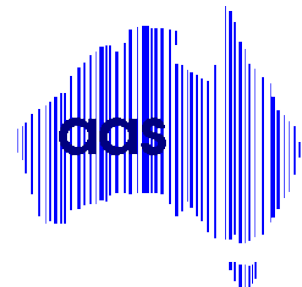
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Wednesday 2 November 2011

**ACOUSTICS 2011**

**Registration**

**Short Course**

**Technical Tour**

**Official Opening and Welcoming Function**

**Short Course: *Environmental Noise Assessment***

8:30		<b>Basic Noise Theory</b> Presenter: Ron Rumble
10:30		Morning Tea
11:00		<b>Computer Modelling</b> Presenter: Peter Karantonis
13:00	<b>Registration</b>	<b>Technical Tour: <i>Whale Watch Cruise</i></b> Lunch
14:00		<b>Legislation</b> Presenter: Michael Hayne
15:30		Afternoon Tea
15:45		<b>Development Assessment</b> Presenter: Ron Rumble
16:45		<b>Open Forum</b> Moderator: Ron Rumble
17:00		Close Shortcourse
17:30	Disembark Surfers Paradise Wharf 17:30	
19:00	Official Opening ACOUSTICS 2011 and Welcoming Barbeque	

## Thursday 3 November 2011

### ACOUSTICS 2011 Session 1

7:00	Breakfast			
8:00	Registration			
8:55	Conference Introduction - Boulevard 1			
9:00	<p>Plenary 1: Dr. David Hiller  <i>005: The prediction and mitigation of vibration impacts of tunnelling</i>            Chair: Matt Terlich            Boulevard 1</p>			
	<p>Session 1A Infrastructure Development            Chair: Claire Richardson            Boulevard 1</p>	<p>Session 1B: Sleep disturbance &amp; health effects            Chair: Russ Brown            Boulevard 2</p>	<p>Session 1C: Room Acoustics            Chair: Ron Rumble            Boulevard 3</p>	<p>Session 1D: Noise and Vibration Control I            Chair: Ben Cazzolato            Palm 3 (Level 3)</p>
9:45	<p>033: <i>Measurement and Prediction of Construction Vibration Affecting Sensitive Laboratories.</i>            Kai Fisher</p>	<p>107: <i>Disturbances of sleep by noise.</i> (Keynote). B. Greifahn</p>	<p>70: <i>Decay Envelope Manipulation of Room Impulse Responses: Techniques for Auralization and Sonification.</i>            Doheon Lee</p>	<p>64: <i>Adaptive-passive quarter-wave tube resonator silencer.</i>            Carl Howard</p>
10:05	<p>108: <i>Construction Noise Management for Hinze Dam Stage 3</i>            Joseph Lee</p>		<p>85: <i>The impact of head-tracking in virtual room acoustic simulations for egocentric sound source.</i>            Manuj Yadav</p>	<p>65: <i>Computational optimisation of the acoustic performance of mufflers for sleep apnoea devices.</i>            Peter Jones</p>
10:25	<p>026: <i>Construction Noise Management Plans: A case study</i>            Chris Schulten</p>		<p>114: <i>Strategic Level Assessment of the Health Effects of Environmental Noise.</i>            Lex Brown</p>	<p>72: <i>Comparison of Room Acoustic Measurements of Diffuseness with a Theoretical Model.</i>            David Spargo</p>

**Thursday 3 November 2011**  
**ACOUSTICS 2011 Session 2**

10:45 Morning Tea (Trade Exhibition Area)					
Session 2A: Non-Destructive Testing Chair: Martin Veidt Boulevard 1	Session 2B Sleep Disturbance Workshop Boulevard 2	Session 2C: Music Acoustics Chair: Ben Hall Boulevard 3	Session 2D: Noise Control Elements Chair: Ian Hillock Palm 3 (Level 3)		
11:10	102: <i>Damage Assessment of Composite Archery Arrows.</i> Ben Cazzolato	Chair: Russ Brown Panel: Lex Brown Frank Henry Barbara Greifahn	142: <i>The acoustics of registers and resonances in singing.</i> John Smith (Keynote)	92: <i>Micro-perforated sound absorbers in stretched materials.</i> Christian Nocke	
11:30	138: <i>Damage Detection in Layered Concrete Structures.</i> Mitchell Willcocks (Invited: Acoustics Bursary, Qld Div)			77: <i>A Review of Acoustic Absorption Mechanisms of Nanoscopic Fibres.</i> Md. Ayub	
11:50	45: <i>Effect of insulation paper ageing on the vibration of electrical conductors.</i> Ming Jin			71: <i>The Loudness Envelope of the Messa di Voce.</i> Densil Cabrera	113: <i>Building Material Panel Sound Reduction Index Evaluation using an Impedance Tube.</i> Stephen Collings
12:10	35: <i>Optimally Parametrized Wavelet Transform for Machine Residual Life Prediction.</i> Muhammad Farrukh Yaqub			82: <i>Correlations among subjective performance qualities and objective acoustical parameters of the didjeridu.</i> Joe Wolfe	16: <i>Investigations of Tuned Vibration Absorber with High Damping for Increasing Acoustic Panels Sound Transmission Loss in Low Frequency Range.</i> Karel Ruber



**Thursday 3 November 2011**

**ACOUSTICS 2011 Session 3**

12:30	LUNCHEON (Trade Exhibition Area)			
13:30	Plenary 2: James Lynch 025: <i>Acoustical Oceanography and Shallow Water Acoustics</i> Chair: Alec Duncan Boulevard 1			
	Session 3A: Underwater Acoustics I Chair: Alec Duncan Boulevard 1	Session 3B: Descriptors and Metrics Chair: Peter Heinze Boulevard 2	Session 3C: Infrastructure Development Chair: Gillian Adams Boulevard 3	Session 3D: Noise and Vibration Control II Chair: Jia Pan Palm 3 (Level 3)
14:15	128: <i>Listening to the ocean: insights into marine animals and the ocean environment.</i> Douglas H. Cato (Keynote)	52: <i>The Evolution of Aircraft Noise Descriptors over the Past Decade.</i> David Southgate (invited)	42: <i>Rail Transit Noise and Vibration Impacts – Why Environmental Planning Doesn't Always Work.</i> Steven Wolfe (keynote)	62: <i>A new cost function algorithm for adaptive passive vibration and acoustic resonators.</i> Carl Howard
14:35		58: <i>In Search of Better Measurement Statistics for Environmental Noise.</i> Huub Bakker		69: <i>Performance evaluation of an active headrest using the remote microphone technique.</i> Ben Cazzolato
14:55	49: <i>Recent Developments in Modelling Acoustic Reflection Loss at the Rough Ocean Surface.</i> Adrian Jones	6: <i>A brief review of road traffic noise indicators and correlations with the LA10(18hour).</i> Daniel Naish	67: <i>The Clem7 Motorway Tunnel: Mechanical and Electrical Plant Acoustic Design and Performance.</i> Claire Richardson	56: <i>Hybrid Passive/Active Inertial Actuators to Attenuate the Structural and Acoustic Responses of a Submerged Hull.</i> Peter Gangemi
15:15	12: <i>Coupled Fluid-Structure Interactions Using the Fast Multipole Method.</i> Daniel Wilkes	78: <i>Government Environmental Noise Policy – A Personal Account of the Last 40 Years.</i> Roger Treagus	130: <i>Noise constraints for coal seam gas development and operations.</i> John Savery (Invited)	96: <i>Design and Evaluation of a Pole Placement Controller for Controlling Vibration of Structures.</i> Xia Pan

**Thursday 3 November 2011**  
**ACOUSTICS 2011 Session 4**

15:35	Afternoon Tea (Trade Exhibition Area)			
	Session 4A: Underwater Acoustics II Chair: Adrian Jones Boulevard 1	Session 4B: Environmental Noise Chair: Dan Naish Boulevard 2	Session 4C: Vibrations Chair: Boulevard 3	Session 4D: Flow Induced Noise I Chair: David Mee Palm 3 (Level 3)
16:00	87: <i>How Wrong Can You Be? Can a Simple Spreading Formula Be Used to Predict Worst-Case Underwater Sound Levels?</i> Alec Duncan (invited)	115: <i>Soundscapes and Soundscape Planning.</i> Lex Brown (Invited)	21: <i>On the symmetry of the impedance matrix for acoustic radiation modes and sound power evaluation.</i> Herwig Peters	44: <i>Empirical Study of the Tonal Noise Radiated by a Sharp-edged Flat Plate at Low-to-moderate Reynolds Number.</i> Danielle Moreau
16:20	22: <i>A dynamic configurable sensor for fractional-octave-band underwater acoustic measurements.</i> Matthew Legg	37: <i>Noise Reduction through Facades with Open Windows.</i> Mitchell Ryan (invited: RJ Hooker Bursary, QLD Div)	34: <i>Finite Element Modelling of the Vibration of a Power Transformer.</i> Yuxing Wang	46: <i>The Effect of Trailing Edge Serrations on Flat Plate Self-noise at Low-to-moderate Reynolds Number.</i> Danielle Moreau
16:40	120: <i>Subarray Beamforming for Reducing the Effect of Flow Noise on Sonar Arrays.</i> James Leader	15: <i>Application of environmental criteria and the Queensland Development Code to proposed development contiguous with transport corridors.</i> Arthur Hall	111: <i>Gearbox Fault Simulation using Finite Element Model Reduction Technique.</i> Lav Deshpande	47: <i>Analysis Of Noise Generated By A Wall-Mounted Finite-Length Airfoil.</i> Narasimha M Thota
17:00	134: <i>Conceptual development of a dynamic underwater acoustic channel simulator.</i> Michael Caley	Workshop <b>BUILDING DESIGN FOR TRANSPORTATION NOISE: TECHNICAL ACOUSTICS AND POLICY, GETTING THE BALANCE RIGHT</b> Chair: Daniel Naish	95: <i>Development of a magnetic levitation vibration isolator using inclined permanent magnetic springs.</i> Yann Frizenschaf	43: <i>Turbulent Trailing Edge Noise Estimation Using a RANS-based Statistical Noise Model.</i> Cristobal Albarracin
17:20	97: <i>Echo time spreading and the definition of transmission loss for broadband active sonar.</i> Yong Zhang	Panel: Dave Southgate Roger Treagus Stephen Pugh Arthur Hall	116: <i>Analytical Modelling of Single and Two-Stage Vibration Isolation Systems.</i> Stephen Moore	53: <i>Multipole Moment Preserving Condensation of Flow Induced Quadrupole Acoustic Sources.</i> Paul Croaker
17:40	Close Day 1			

**Thursday 3 November 2011**

***Australian Acoustical Society Annual General Meeting***

***ACOUSTICS 2011 CONGRESS DINNER***

18:00

***Australian Acoustical Society Annual General Meeting (Palm 3)***

19:00

**Cocktail Reception (Boulevard Pre-function Area)**

19:30

***ACOUSTICS 2011 CONGRESS DINNER***

Speaker: Joe Wolfe

23:30

**Friday 4 November 2011**  
**ACOUSTICS 2011 Session 5**

7:00	Breakfast			
9:00	<p>Plenary 3: Professor David Thompson  009 <i>The role of theoretical models in shaping railway noise policy and mitigation strategies.</i>  Chair: Paul Meehan  Boulevard 1</p>			
	<p>Session 5A: Rail Noise I  Chair: Paul Meehan  Boulevard 1</p>	<p>Session 5B: Wind Turbines I  Chair: Matt Terlich  Boulevard 2</p>	<p>Session 5C: Road Traffic Noise I  Chair: Steve Pugh  Boulevard 3</p>	<p>Session 5D: Flow Induced Noise II  Chair: Con Doolan  Palm 3 (Level 3)</p>
9:45	<p>40: <i>Predicting variable speed rail corrugation growth using statistical moments.</i>  Ross Batten</p>	<p>50: <i>Comparison of Compliance Results from the Various Wind Farm Standards Used in Australia.</i>  Jonathan Cooper</p>	<p>110: <i>Traffic Noise Prediction with Nord2000 – An Update.</i>  Jørgen Kragh (Keynote)</p>	<p>54: <i>A Simple Approach to Estimate Flow-Induced Noise from Steady State CFD Data.</i>  Paul Croaker</p>
10:05	<p>51: <i>Railway rolling noise prediction under European conditions.</i>  Shijie Jiang</p>	<p>29: <i>Contribution of Wind Farm Into Noise at a Distant Receiver in a Rural Environment.</i>  Byron Holmes</p>		<p>48: <i>On the equivalence of the Ffowcs Williams – Hawkings and the non-uniform Kirchhoff equations of aeroacoustics.</i>  Alex Zinoviev</p>
10:25	<p>Rail workshop session 1</p>	<p>30: <i>Comparison of Predicted and Measured Wind Farm Noise Levels and Implications for Assessments of New Wind Farms.</i>  Tom Evans</p>	<p>100: <i>Noise level variation in the CBD with height.</i>  Sangarapillai Kanapathipillai</p>	<p>105: <i>The Characteristics of Sound Radiation by Turbulent Flow over a hydrofoil and a bare-hull Suboff.</i>  Li Chen</p>

**Friday 4 November 2011**  
**ACOUSTICS 2011 Session 6**

10:45 Morning Tea (Trade Exhibition Area)				
	Session 6A Rail Noise II Chair: Dave Anderson Boulevard 1	Session 6B: Wind Turbines II Chair: Christophe Delaire Boulevard 2	Session 6C: Road Traffic Noise II Chair: Arthur Hall Boulevard 3	Session 6D: Structural Vibration Chair: Nicole Kessissoglou Palm 3 (Level 3)
11:10	98: <i>Groundborne Noise and Vibration Control at Performing Arts Centers using Elastomeric Bearings.</i> Steven Wolfe	17: <i>Concepts for the control of wind turbine noise.</i> Con Doolan	39: <i>Prediction of Carpark Noise in Australian Conditions.</i> Laurence Nicol	141: <i>Analysis of underwater vibration of a torpedo-shaped structure subjected to an axial excitation.</i> Jie Pan
11:30	38: <i>Reducing Secondary Noise On Nanjing Metro, China.</i> Steve Barlow	57: <i>Problems Measuring Low Frequency Sound Levels Near Wind Farms.</i> B. Rapley	Workshop: Low Noise Road Surfaces  Panel: Arthur Hall Steve Pugh	66: <i>The Effect of Distribution for a Moving Force.</i> Ahmed Reda
11:50	88: <i>A numerical study to evaluate dynamic responses of voided concrete sleepers to impact loading.</i> Sak Kaewunruen	73: <i>Wind Turbine Noise: why accurate prediction and measurement matter.</i> Bob Thorne		123: <i>Structural vibration transmission in stiffened structures.</i> James Forrest
12:10	Rail workshop session 2	119: <i>The Peril of Ignoring Insect Noise in the Assessment of Ambient Noise Levels.</i> Matthew Terlich		36: <i>Vibration characteristics of a cylinder with asymmetries.</i> Heye Xiao

**Friday 4 November 2011**  
**ACOUSTICS 2011 Session 7**

12:30	LUNCHEON (Trade Exhibition Area)			
	Session 7A Rail Noise 3 Chair: David Thompson Boulevard 1	Session 7B: Wind Turbines and Low Frequency Noise Chair: Norm Broner Boulevard 2	Session 7C: Directivity and Response Chair: David Spearritt Boulevard 3	Session 7D: Acoustical Sensor Networks Chair: Michael Hayne Palm 3 (Level 3)
13:30	122: <i>Recent Developments in the Practical State-of-the-Art in Managing Rail Noise in Australia.</i> Dave Anderson (invited)	28: <i>A Preliminary Investigation Into The Determination Of The Inaudibility Level Of Mechanical Plant And Music Noise In The Presence Of Ambient Background Noise.</i> Rodney Phillips	99: <i>Practical Considerations for Designing Road Tunnel Public Address Systems.</i> Peter Patrick (invited)	89: <i>Fibre optic acoustic sensing for intrusion detection systems.</i> Gary Allwood
13:50	19: <i>Some Pitfalls in Using AS2377-2002 for Passby Noise Measurement.</i> David Hanson	23: <i>Low-frequency and Tonal Characteristics of Transformer Noise.</i> Michael Gange	137: <i>Road tunnel acoustics.</i> Peter Ridley	139: <i>Development of a Photo-Acoustic Trace Gas Sensor.</i> Christopher Kelly (invited: RJ Hooker Bursary, QLD Div)
14:10	79: <i>Investigation about the effect of angle of attack and relative humidity on wheel squeal.</i> Xiaogang Liu	Workshop: Wind Turbines and Low Frequency Noise Chair: Norm Broner	76: <i>Close-range variation in binaural responses to orally-radiated sources.</i> William Martens	93: <i>Sound Monitoring Networks New Style.</i> Dick Botteldooren
14:30	75: <i>Determination of track decay rate using field trials.</i> Wenxu Li		136: <i>Applicability of spherical microphone arrays in room acoustics.</i> Magdalena BOECK	14: <i>UAV-Based Acoustic Tomography.</i> Anthony Finn
14:50	Rail workshop session 3		94: <i>Acoustic source beam control using a compact virtual loudspeaker array.</i> Ken Stewart	106: <i>Acoustics and the Smart Phone.</i> Rhys Brown

**Friday 4 November 2011**  
**ACOUSTICS 2011 Session 8**

15:10	Afternoon Tea (Trade Exhibition Area)	
	<p>Session 8A Marine Bio-Acoustics          Chair: Doug Cato          Boulevard 1</p>	<p>Session 8B: Psychoacoustics and Design          Chair: Chris Schulten          Boulevard 2</p>
15:40	<p>101: <i>Acoustic methods to mitigate bycatch and depredation by marine mammals on commercial fishing operations in Australian waters: Fishermens options.</i>          Geoff McPherson (invited)</p>	<p>140: <i>Noise level assessments: Subjective vs objective measures.</i>          Elizabeth Beach</p>
16:00	<p>127: <i>Detection of beaked whale clicks in underwater noise recordings.</i>          Iain Parnum</p>	<p>3: <i>Emergency Vehicle Auditory Warning Signals: Physical and Psychoacoustic Considerations.</i>          Aaron Maddern</p>
16:20	<p>91: <i>Measurements Of Snapping Shrimp Noise Along The Cooks River, Sydney.</i>          Marshall Hall</p>	<p>133: <i>Prediction of noise from Small to Medium Sized Crowds.</i>          Michael Hayne</p>
16:40	<p>27: <i>Underwater environmental impact assessments on marine mammals and fishes from sound radiated by anthropogenic noise.</i>          Antoine David</p>	<p>112: <i>Acoustic Design Approach for Hospitals.</i>          Samuel Clarke</p>
17:00	Close Day 2 - Conference Closes	