THE ACOUSTIC RADIATION FROM PAVEMENT JOINT GROOVES BETWEEN CONCRETE SLABS

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ABSTRACT

The sound generation and radiation from grooves in the joints between concrete slabs were modeled using relationships previously established for tire groove resonances and groove air pumping. Resonant behavior was clearly established from both in-lab and on-road on-board sound pressure level data. The strength of the noise source was found to be proportional to 20 times the logarithm of the groove cross-sectional area. This relationship along with the accounting of residual texture, background noise was found to replicate that measured in the lab testing. The model was then calibrated using the lab results and extended in speed range using a theoretical calculation of the sound radiation from the end of the joint groove. The predicted level produced by an isolated joint of specified dimension was then used to model the average sound intensity level for a pavement with a user specified distance between joints, vehicle speed, and pavement texture generated noise level. For smaller groove cross sectional areas (~ 0.25 in^2), the contribution of joint grooves was found to be on the order of 1 dB for quieter pavement textures. For larger cross sectional areas, such as a groove width of ½ inch and depth of 1 inch, the contribution increases to almost 3 dB.

INTRODUCTION

Impulsive noise associated with the passage of the tires over the joints between in Portland cement concrete (PCC) pavement as been noted by a number of researchers lately some of which has been reported in the literature[1]. Examples of the impulses are shown in Figure 1 for two different PCC highway surfaces in California, an older longitudinally textured pavement (I-80) and new longitudinally broomed textured pavement (Mojave SR 58). In this figure, the

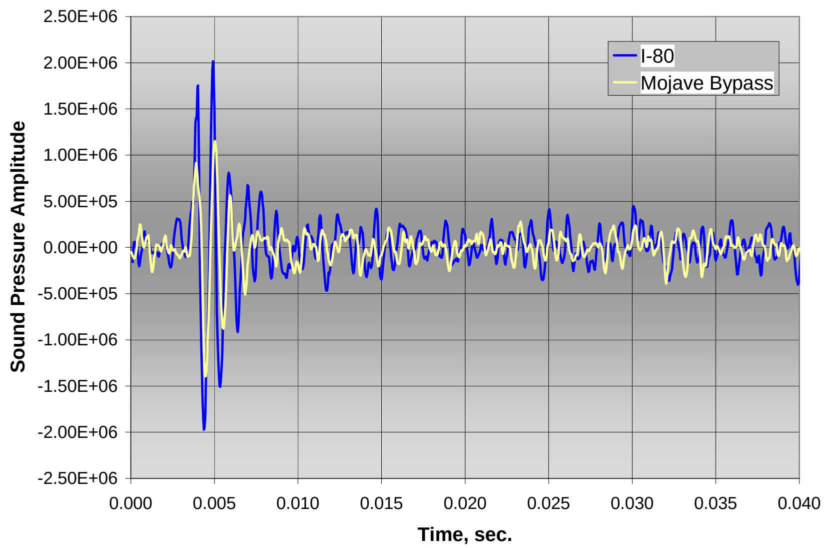

Figure 1: Joint slap for 2 different California PCC pavements – sound pressure vs time

impulses, beginning at about 0.004 seconds, are clearly higher than the residual sound pressure occurring after 0.010 seconds due the pavement texture only. Depending somewhat on the pavement, the impulse persists for about 0.005 seconds and, particularly for the I-80 example, the time histories display "ringing" or oscillatory resonate behavior that decays away with time. The ringing occurs with about the same repetition rate (0.001 seconds) for both cases at least through the first three oscillations. Also, in both cases, the initial pressure rise is slightly less in absolute amplitude than the second peak as well as the negative peak in the impulse. Another indication of a resonant phenomenon is the observation that the period of oscillation is not effected by vehicle speed as shown in Figure 2 for the broom texture surface.

To understand the generation of the noise by PCC joints, the American Concrete Paving Association recently sponsored research at Purdue University[2]. This work utilized the Tire-Pavement Test Apparatus (TPTA) to measure the effect of different joint parameters in carefully controlled laboratory conditions. The effects of joint width and joint depth were evaluated along with the effect of pavement slab offset. A typical time trace for passage over a joint is provided in Figure 3 for a case where no slab offset is present and the groove is 3/8 inches (9.5 mm) wide and 1 inch (25.4 mm) deep for a test speed of 30 mph (48 km/h). Comparing this trace to that of Figure 1, several similarities can be noted. As in the previous case, the trace of Figure 3 indicates an oscillatory behavior with approximately the same repetition rate of 0.001 second.

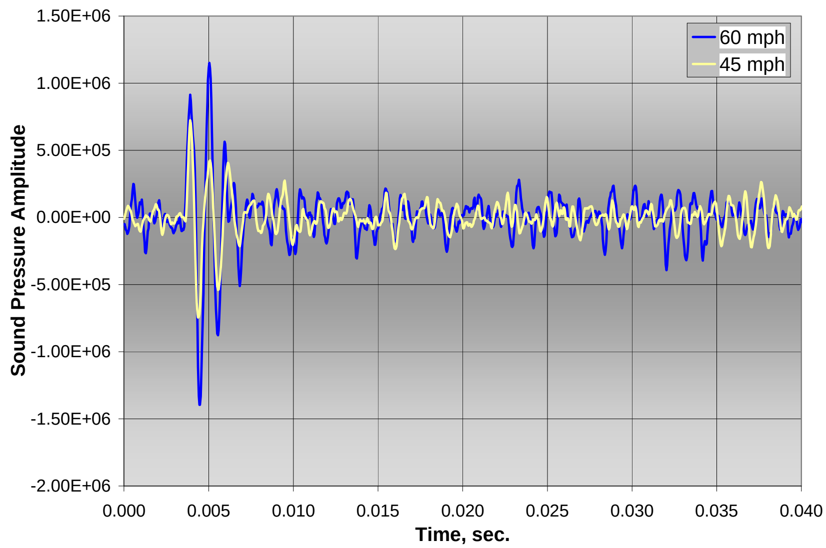

Figure 2: Joint slap for Mojave Bypass pavement at 60 and 45 mph

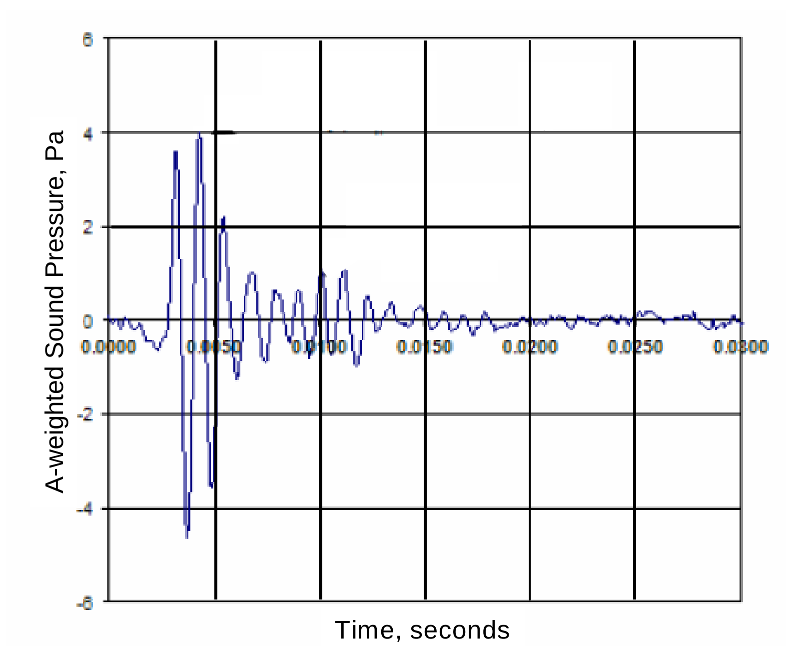

Figure 3: Joint slap recorded on the Purdue TPTA at 30 mph (Ref. 2)

The TPTA case also decays with time and the initial positive pressure rise is slightly less than the negative peak or second positive peak. The higher levels associated with the event, however, last about twice as long as they do for 60 mph (97 km/h) case of Figure 1, about 0.01 second at 30 mph versus 0.005 second at 60 mph. Given a tire footprint length of about 5.3 in. (135 mm), these times correspond approximately to the time duration that the tire is actually covering the joint.

In this paper, a model of sound generation due to the passage of a tire over a PCC joint is developed and some the indicated trends are presented. In doing this, the results from the Purdue University study are used to validate the theoretical trends documented and to calibrate the model for noise prediction. This work also draws on research work that was completed at the General Motors Research Laboratories in the late 1970's and early 1980's that considered sound generation and radiation from grooves in tires[3,4].

MODEL DEVELOPMENT

The physics of the model is illustrated in Figure 4. Simply stated, the tire rolls over the joint squeezing air out of the channel and forms an "organ pipe" open at two ends. The sound radiation is produced by the initial pumping of air out of the groove and is maintained by organ pipe resonances that persist until the tire lifts off of the joint. The corresponding mechanisms for grooves in tires operating on uniform pavement have been documented for both longitudinal

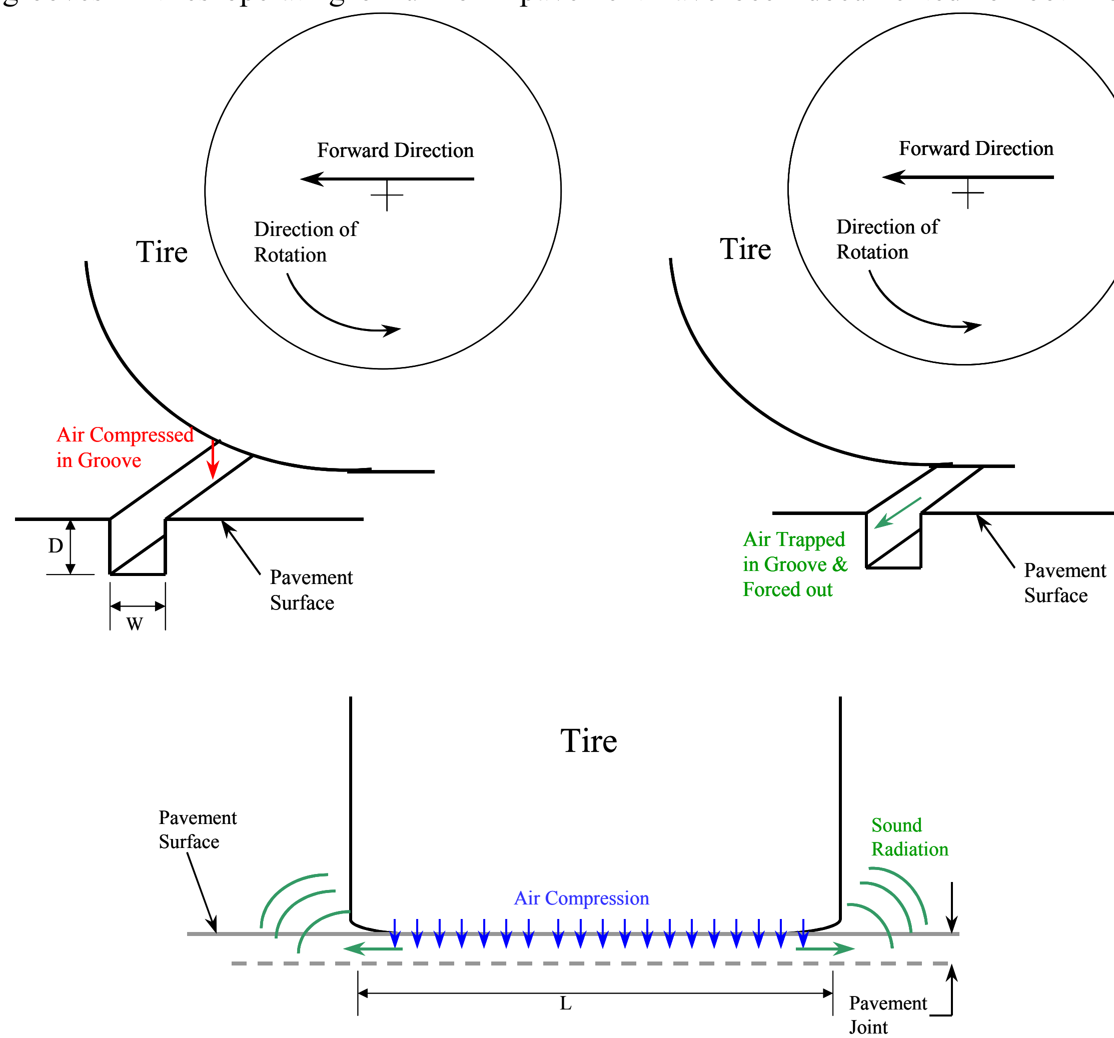

Figure 4: Illustration of the envelopment of pavement groove, related geometry, and noise mechanism from the side and through the cross-section

(circumferential) grooves in tires[4] and lateral grooves[3]. Developing the model concerns three aspects: accounting for the groove resonances, determining the source strength of air displacement, and finally calibrating the model.

Groove Resonance

In terms of sound radiation and resonate behavior, the circumferentially ribbed tire (Figure 5) is directly analogous to the PCC joint problem[4]. In both cases, the organ pipes formed are open on both ends. When the cross sectional dimensions of the pipe are small compared to an

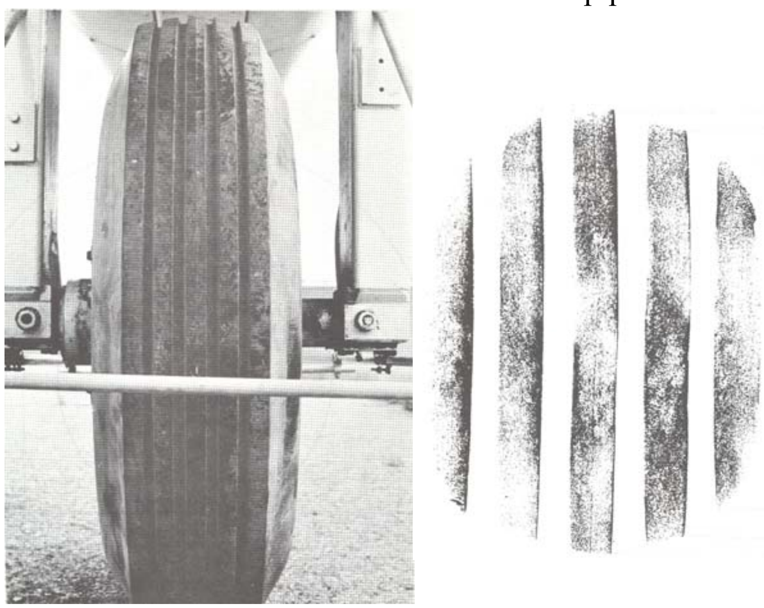

Figure 5: Photograph and contact patch of a straight-ribbed HCR Truck Tire (Ref. 4)

acoustic wavelength, the resonances or standing waves in the pipes occur at specific frequencies defined by:

$$f_n = (n*c)/(2*L) \quad \text{for } n = 1, 2, 3, \ldots.. \qquad (1)$$

where f_n is the frequency of the nth mode, L is the length of the organ pipe, and c is the speed of sound. For an ideal pipe, the sound pressure at the ends of the pipe is 0 and for the first mode, a maximum in pressure occurs in the middle of the pipe. For higher modes, pressure alternates from being at a maximum at the center pipe to being zero at the center. In the ideal case, the acoustic particle velocity is exactly 90° out of phase with the pressure producing maximum levels at the exits to the pipe. In real cases, such as for tire/pavement noise, the terminations of the pipe are not ideal and not well defined. For the case of circumferential straight ribs, an effective pipe length is given by:

$$L_{eff} \approx L + 2*(0.6*[(s/\pi)^{1/2}]) \qquad (2)$$

where s is the cross sectional area of the pipe. This effective pipe length has been found to provide reasonable agreement with experimental results and the behavior has been shown to vanish when the grooves are filled with light weight foam (Figure 6)[4]. For the two tires used in the Purdue study (P205/70R15 Uniroyal Tiger Paw and Goodyear Aquatred 3), the width of the

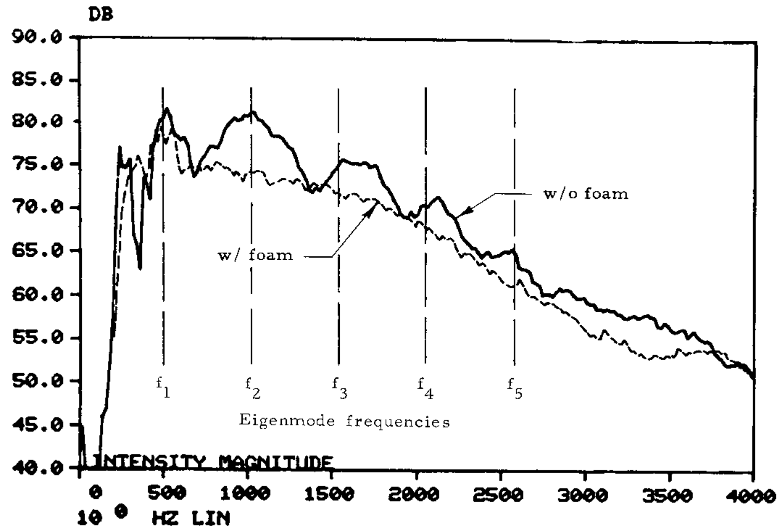

Figure 6: Influence of groove resonance for a straight rib tire sound intensity level with and without foam in the ribs

contact patch is approximately 5.5 in. and 6.1 in. (140 and 155 mm), respectively. For the Aquatred, this leads to an effective length of 0.166 m. As a result, the frequencies of the first 4 modes are f_1=1039 Hz, f_2=2078 Hz, f_3=3117 Hz, and f_4=4156 Hz. It will be noted from the expression for f_n that when the cross sectional area of the pipe (or groove) is small compared to the length L, as it does in this case, that the resonant frequency is determined only by the width of the tire contact patch. As a result, only very small differences in the resonant frequencies would occur for changes in the width and depth of the groove. This implies that for a given tire, the resonant frequencies would be essentially the same independent of the joint geometry. This is partially confirmed by the time traces of Figures 1 and 3, which correspond to joint widths of approximately ⅛, ⅜, and ½ inch for the I-80, Purdue, and Mojave joints, respectively. In the Purdue investigations, it was also noted that the shape of the frequency spectra did not shift with joint dimension or tire passage velocity[5].

In comparing the sound generation and radiation between circumferential rib tire and transverse joint in the PCC pavement, some differences do exist in the source of the excitation of the "organ pipes". For the rib tire, the relative flow through the tube due to the rolling tire does not produce acoustic excitation as the process is continuous. For this tire, the excitation is supplied by vibration of the tire tread forming three of the sidewalls of the tube. This vibration is induced by pavement roughness and to a lesser degree by shear stresses produced in the rolling tire[6]. For the pavement joint, the initial excitation is created by abrupt volume change as the tire seals against the pavement groove. This excitation process is analogous to that produced by a transverse groove in a tire, typically called tread pattern "air-pumping"[3] as illustrated in Figure 7. Although the excitation mechanism is similar between the transverse joint and the transverse tread element, the resonance characteristic is different as the tread element pipe is closed on one end and open on the other. This has the effect of eliminating the even number modes from Eqn. 1. This arises from the boundary condition that at the closed end of the tube, the acoustic velocity must be zero and pressure at a maximum. Enforcing this condition on the pressure mode shapes for tread groove, only the 1st and 3rd modes meet this requirement for closed tube

Open groove Groove closed, forming tube Volume change in groove

Figure 7: Illustration of the noise mechanism for open/closed end tube in a tire tread passing through the tire contact patch (Ref. 3)

equal in length to L/2 (i.e. maximum pressure at center of length L). It should be noted that in terms of analyzing source strength from due to the forcing of air out of the groove, because of symmetry, the analysis of closed end tube of length L/2 is identical to that of the open tube of length L.

Source Strength Analysis

The driving force for the source strength of the both the tire and pavement groove is the change in volume as the air is expelled from the groove. This change in volume results in air motion at the open end of the tube that in turn results in an acoustic pressure pulse. The pressure at some distance r alongside the tire can be expressed as[3]:

$$p(r, t) = (1/r\pi)*\rho*D*W*(dv_L/dt) \tag{3}$$

where ρ is the density of air, D and W are defined in Figure 4, and v_L is the acoustic velocity at the end of the tube. In terms of the groove, the variables of importance are the groove dimensions D and W and the rate of change of the velocity at the end of the tube. For fixed dv_L/dt, the pressure is directly proportional to the cross sectional area of the groove. Using this expression, the relative effect of the increasing groove width and/or depth can readily be determined as:

$$SPL \propto 20*Log[p(r, t)] \propto 20*Log(D*W) \tag{4}$$

where SPL is the relative sound pressure level. With this relationship, relative SPL as a function of either groove width or depth can be plotted for different values of each. With this simple expression and the addition of a background noise corresponding to that of the TPTA, the results from the Purdue were approximately matched. In the TPTA results, the increase in level for a ¼ inch wide, 1 inch deep groove to a 1 inch wide groove was on average 8.4 dB with a standard deviation of 1.5 dB[2]. The modeled result using Eqn. 4 with the TPTA texture background noise of 91 dBA was 8.9 dB.

The other feature of Eqn. 3 is the dependence on the air velocity time derivative at the exit of the groove. This velocity is directly related to the rate of change of air volume in the groove. This rate of change is also a function of how rapidly the tire envelops the groove. The transfer function that relates volume change to v_L is also dependent on frequency corresponding to the modes of the groove. To examine this transfer function, the instantaneous air volume (q[t]) in the initial open groove is considered. The rate of change of this quantity then has a relationship to the rate of change of the air particle velocity at the open end of the tube. This relationship can be expressed in the frequency domain through the Fourier Transform, $Q(\omega) = \Im[q(t)]$ where ω is the angular frequency, $\omega = 2\pi f$. Similarly, the particle velocity at L is given as $V_L(\omega) = \Im[v_L(t)]$. These two quantities are related to each other through a complex transfer function, $T_1(\omega)$:

$$V_L(\omega) = T_1(\omega) * Q(\omega) \tag{5}$$

It can be shown that the expression for $T_1(\omega)$ is given by[2]:

$$T_1(\omega) = c^2 * (2/L) * \sum_j 1/(\omega_j^2 - \omega^2) + i\omega * (2\delta_j * \omega_j) \quad \text{for } j=1, 2, 3, \ldots \text{ to } \infty \tag{6}$$

with ω_j given by Eqn. 1, i indicating an imaginary number ($i=\sqrt{-1}$) , and

$$\delta_j = (R/2 * \rho * \omega_j) \tag{7}$$

where R is the flow resistance taken as 366 Ns/m^4 for air in the tube. Using the effective tube length defined by the tire contact patch width, the magnitude of the transfer function $T_1(\omega)$ is provided in Figure 8. From this figure, it is shown that the modal structure cited in regard to Eqns. 1 and 2 is retained.

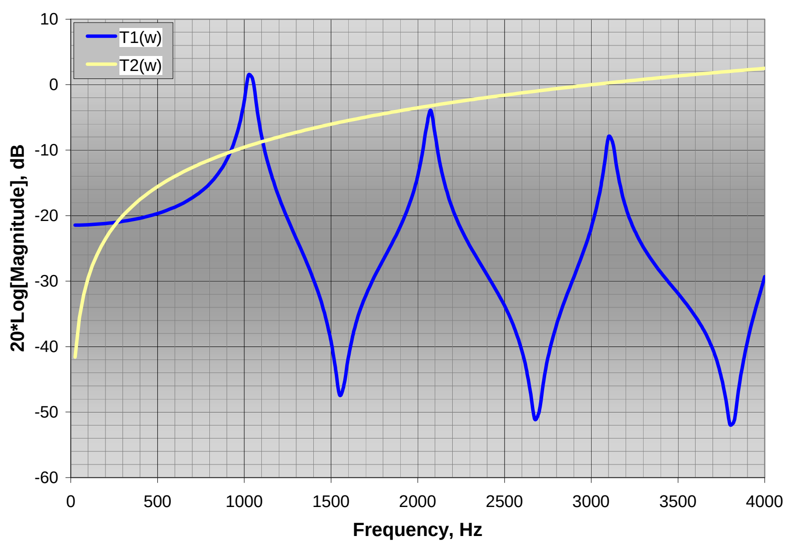

Figure 8: Magnitude of transfer functions between volume change and air velocity at the opening of the groove, $T_1(\omega)$, and the transfer function between air velocity and sound pressure, $T_2(\omega)$

The sound pressure at r alongside the tire as defined by Eqn. 3 can also be expressed as its Fourier transform, P(r,ω). This sound pressure is then related to the air velocity at the end of the tube by:

$$P(r,\omega) = V_L(\omega)*T_2(\omega) = T_1(\omega)*Q(\omega)*T_2(\omega) \qquad (8)$$

where the transfer function between the acoustic velocity and pressure is given by:

$$T_2(\omega) = i\omega*\rho*D*W*(1/\pi r)*e^{-ir*\omega/2} \qquad (9)$$

The magnitude of this transfer function is also plotted in Figure 8 and is seen to increase monotonically with frequency.

With $T_1(\omega)$ and $T_2(\omega)$ defined, the sound pressure can be solved if $Q(\omega)$ is known. Following the case of the transverse groove, the shape of the volume change pulse for the groove in the pavement application is taken to be of the form:

$$q(t) = (\Delta V/V)*\tfrac{1}{2}*[1-\cos(2*\pi*t/T)] \quad \text{for } T \geq t \geq 0 \qquad (10)$$

$$q(t) = 0 \qquad \text{for all other } t$$

where V is the volume of the groove, ΔV is the change in volume and T is the duration of the volume change. The shape of this function is plotted in Figure 9 starting at time t=0. The full duration of this plot shows the amount of time (0.005 seconds) that the tire contact patch remains

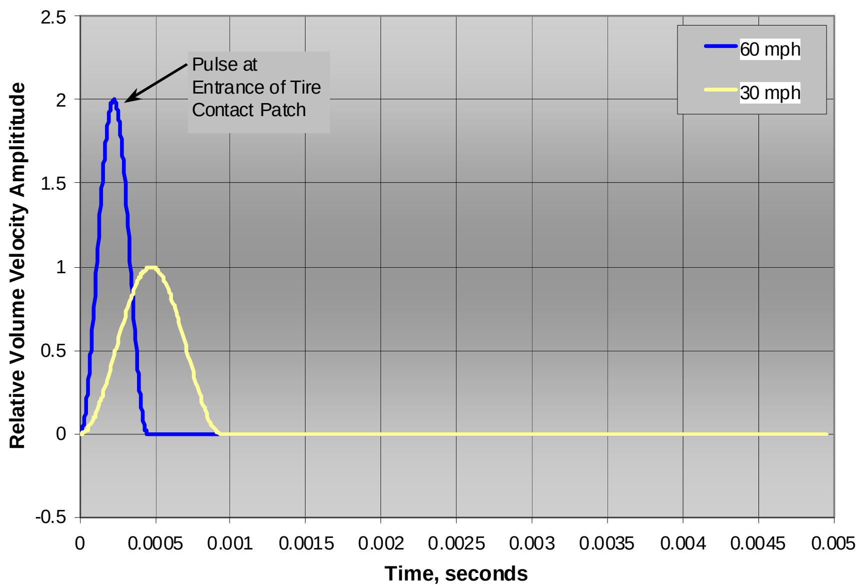

Figure 9: Assumed shape of the volume velocity pulse as the groove is enveloped at 60 and 30 mph

over the groove at 60 mph for the Aquatred tire. For comparison, the volume velocity corresponding to 30 mph is also shown in Figure 9. In this case, the maximum amplitude is reduced by half so the total volume displacement remains equal between the two speeds. The Fourier Transform of Eqn. 10 was taken and values of T equal to 0.00047, 0.00071 and 0.00095 seconds were used to calculate $Q(\omega)$ for 60, 45, and 30 mph, respectively, corresponding to a ½ inch groove width.. The magnitude of the results of these calculations is shown in Figure 10. These results show that for the slower speed, the volume velocity varies

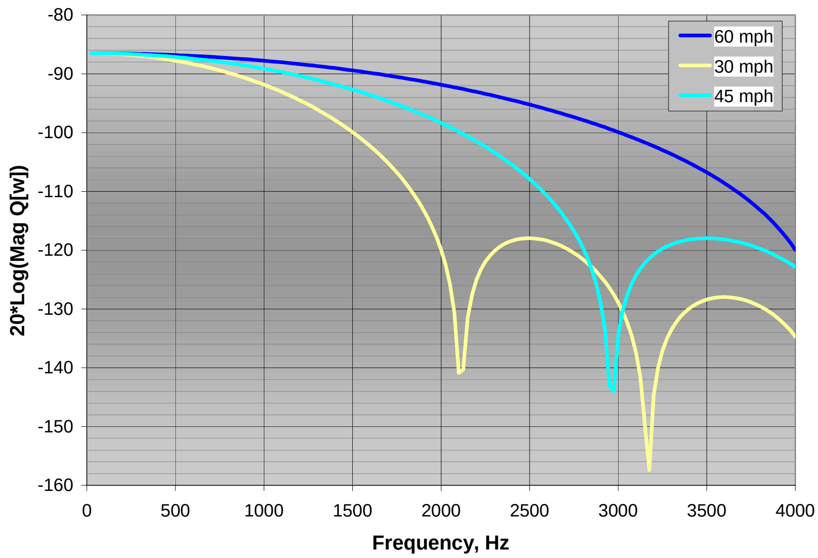

Figure 10: Calculated relative magnitude of the groove volume velocity pulse as a function of frequency for assumed pulse shape at 60, 45, and 30 mph

more with frequency (i.e., not as "flat") up to several thousand Hertz as would be expected for the longer event duration. The magnitude of P(ω) can now be calculated using the already determined transfer functions, $T_1(\omega)$ and $T_2(\omega)$ and are shown in Figure 11 for the speeds of 60, 45, and 30 mph. In these plots, it is apparent how the slower tire speeds reduce the levels at

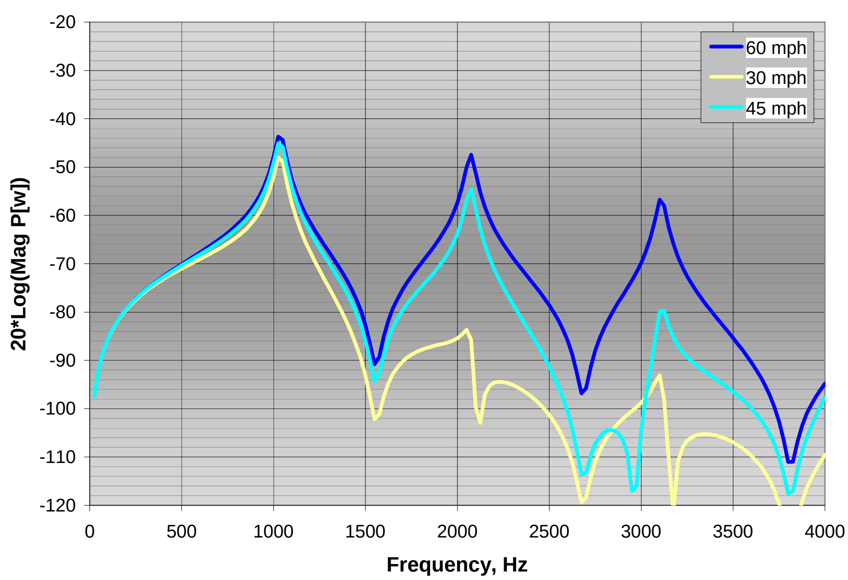

Figure 11: Calculated relative magnitude of the acoustic pressure at the open end of the pavement groove as a function of frequency 60, 45, and 30 mph

frequencies above 1500 Hz. At the resonant peak of the 1^{st} mode (~1000 Hz), a reduction of about 4 dB can be seen between the speeds of 60 and 30 mph. These plots also re-enforce the earlier observation that, at least for the lower tube mode, the frequency peak of the radiated sound is independent of vehicle speed.

Level Calibration

The results of Figure 11 are relative as the absolute magnitude of q(t) is not known. However, using the results of the Purdue research, the model can be calibrated if the sound produced by a slap is isolated for one or more groove geometries. In the Purdue work, the sound pressure levels for a variety of the joint geometries are reported as measured over a 0.08 second window (see Figure 3). This window includes energy from both the groove response and the residual level of the TPTA surface texture. To isolate the groove response, this residual level needs to be removed and energy remaining in the pulse quantified. The Purdue data was reported at speeds of 10, 15, 20, 25, and 30 mph for groove depths of 1 inch, ½ inch, and ⅛ inch and groove widths of 1 inch, ¾ inch, $^{9}/_{16}$ inch, and ¼ inch. These results were curve fit as a function of groove width at each speed and the zero width intercept was used to as residual level. The residual as a function of speed was then subtracted on an energy basis from the results with the various groove cases to extract the isolated groove response for each geometry. Due to the low groove response levels at the ⅛ inch depth relative to the residual texture noise, only the cases of for the 1 inch and ½ inch depth were used. These data were then fit to that predicted by the model for the appropriate geometry for a speed of 30 mph corresponding to the same speed calculated in Figure 11.

To extend the calibration to higher speeds, the results of Figure 11 were used. The differences between the speeds in narrow band levels were summed into ⅓ octave bands and applied to a Mojave burlap drag spectrum. The difference in overall A-weighted was determined and found to be 4.9 dB going from 30 to 60 mph and 1.9 dB going from 45 to 60 mph. As a final step in isolating the pulse, the duration of the groove response relative to the 0.08 second time window is to be taken into account. Differences cited above reflect equal energy summed over the 0.08 period (see Figure 9). To determine the root mean square (RMS) level of the pulse, the energy must be divided by the duration of the pulse. In going from 30 to 60 mph, the energy of the pulse (the sum of the p^2 values) is the same. However, the time period of the summation is half as long at 60 mph than at 30 mph. This result in a ratio of the inverse time periods of 0.010/0.005, which amounts to a 3 dB correction relative to the analysis period of 0.08 seconds. For 45 mph relative to 30 mph, this amounts to 1.2 dB. Including this correction and the earlier adjustment arising from Figure 11, the total difference between 30 and 60 mph is 7.9 dB, and 4.8 dB for 30 to 45 mph. Fitting these results to a logarithmic function with speed, it is found that relationship of groove response with tire operating speed of S is $26.5*\text{Log}_{10}(S)$. Given this relationship and that of Eqn. 4, the sound level of the groove response can be calculated at any speed and groove geometry by using the calibrated level of 99.2 dBA at a speed of 30 mph for a 1 inch wide and 1 inch deep reference groove.

MODEL DESCRIPTION AND RESULTS

With the model calibrated in the manner discussed above, the sound pressure level produced at a chosen speed can be calculated for varying groove geometries. The results of such calculations are shown in Figure 12 for a tire operating speed of 60 mph. As expected from Eqn. 4, this shows the trend that as the groove dimensions increase, the sound level also increases.

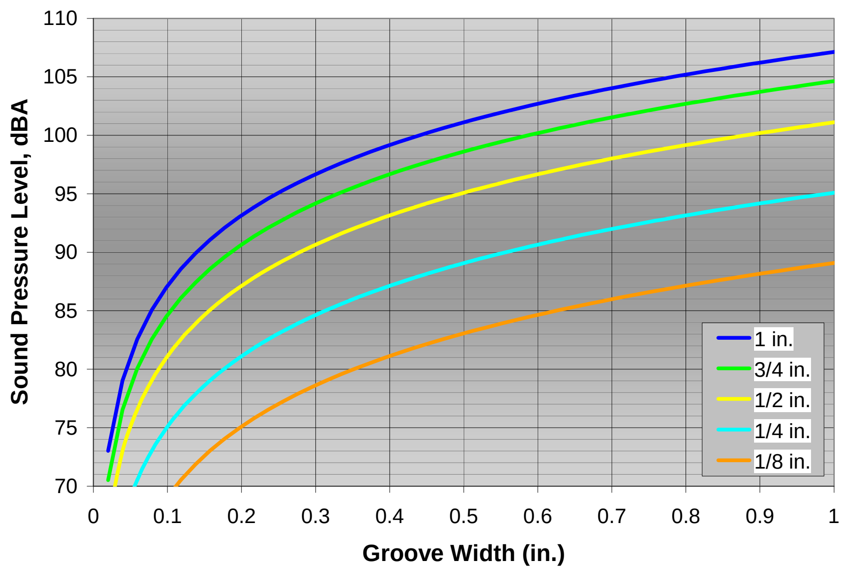

Figure 12: Sound pressure levels calculated for joint grooves of varying dimension at 30 mph using the calibrated model

To apply these to an actual pavement and calculate the overall level time average level, two further parameters are needed. First is the repetition rate of the slaps, which can be determined by the joint spacing and the tire operating speed. The repetition rate in slaps/second is then multiplied by the energy of one pulse and the length of the reference time window, 0.08 seconds, to obtain the average level contribution of the joint grooves. Second is the residual texture noise level of the pavement. The noise level of the pavement is typically measured using the on-board sound intensity (OBSI) in the US. For use with these data, the sound intensity level of the groove response is be taken to be equal to the sound pressure level in this case as the model corresponds to a compact noise source and free field propagation. The overall level for a pavement is energy sum of the groove contribution and the texture generated noise level. An example of this is given in Figure 13 for a case where the joint spacing is 13 feet, the vehicle speed is 60 mph, and the residual pavement texture OBSI level is 99.0 dBA, corresponding to a typical, quieter burlap drag or ground PCC textured pavement. In this case, the joint groove adds about 1 dB to overall level when the groove cross-sectional area reaches 0.25 square inches, or for a groove dimension of ½ inch deep by ½ inch wide. The model can also be used in the reverse calculation. If the overall OBSI is known along with the joint parameters, the residual texture level could be calculated.

The results shown in Figure 13 can be used to give some direction in efforts to reduce the contribution of PCC joint slap to overall levels. If groove width is limited to ⅛ inch, even for relatively low noise texture, the contribution of the joint groove to overall level will be negligible for depths up to at least 1 inch. If filled with sealer to within ⅛ inch of the pavement surface, the contribution of joint grooves can also be made negligible. As an example, for a 1 inch deep by ½ inch wide groove filled to within ⅛ inch of pavement surface, the overall level would be reduced by about 2½ dB given the assumed texture level of 99.0 dBA. It should be noted that for higher texture levels, the contribution of the joint grooves will diminish somewhat. For example using the conditions of Figure 13 but compared to pavement with a residual of 103 dBA and using a

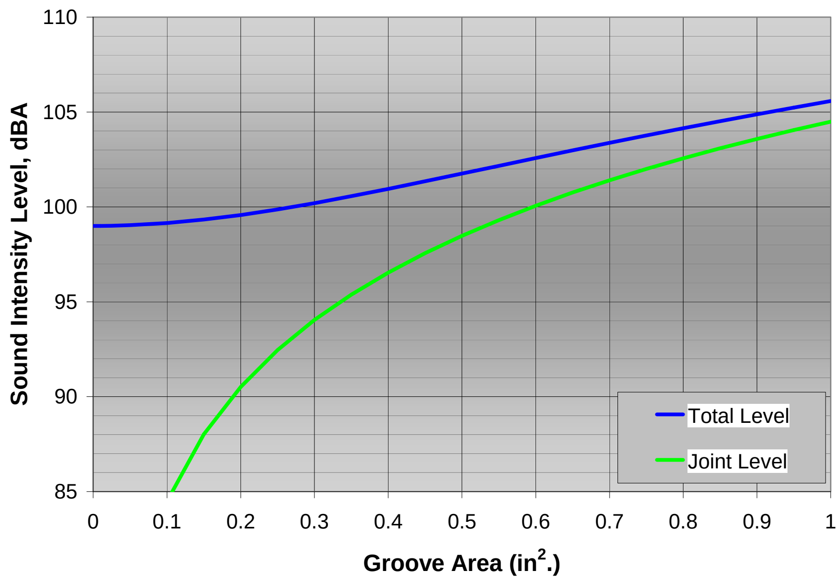

Figure 13: Model results of overall pavement OBSI level for joints spaced 13 feet apart, a vehicle speed of 60 mph, and pavement texture OBSI level of 99.0 dBA

joint groove ½ inch deep by ½ inch wide, the contribution of the joint to the overall level would decrease to 0.4 dB for noisier texture from 0.9 dB for the quieter texture.

In considering the results of this model, it should be realized that the source levels do not include the effect of any offset or "faulting" of the concrete slabs. From the research work done at Purdue, this effect can be quite significant[2]. At 30 mph, it was reported that the level offset alone produced increases in sound pressure level of about 1 dB per 0.025 inches of step height. Because of this effect of slab offset, field validation of the groove effects model is problematic unless it is verified that offsets do not exist. However, the results of model are consistent with those obtained on the Mojave Bypass in the consideration of the contribution of joint slap for longitudinally tined, burlap drag, broomed texture surfaces[7]. In that research, the contribution of joints was determined by trigging a 0.08 second analysis window such that the joint was included and then excluded. The difference in these levels produced isolated level of the joints. These derived joint levels were found not to be dependent on the pavement texture as would be predicted by the model.

CONCLUSIONS

Grooves between PCC pavement slabs can contribute to the total measured noise level, particularly when the noise levels generated by the pavement texture is relatively low. The radiation of sound from the grooves demonstrates the same resonate behavior as that associated with longitudinal, circumferential grooves in tires and to transversely oriented grooves in the tire tread patterns. Drawing upon these cases, the sound radiation from the transverse grooves present between concrete slabs can be modeled and compared to laboratory and road data. The source strength of the groove radiation is proportional to 20 times the logarithm of cross-sectional area. With the consideration of residual noise introduced by the pavement texture, laboratory trends are readily duplicated. Once calibrated for the level produced by single, isolated groove response, the model results can be applied in situations representative of actual highway pavement for determining the contribution of joint grooves to overall pavement noise level. This contribution can be made negligible by minimizing the cross-section area of the groove.

ACKNOWLEDGEMENTS

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