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Tire Sound Quality Prediction – Process Improvements

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ABSTRACT

Tire sound quality has become increasingly important for aftermarket tire manufacturers, as vehicle sound levels continue to decrease and customer expectations of noise performance continue to increase. To continue to develop products to match these expectations, component level manufacturers must develop robust processes to predict the sound quality performance of their components as installed in a vehicle, solely upon component level tests.

This paper serves as an update to a process developed by a major tire manufacturer to predict vehicle level performance of aftermarket tires based upon component level test stand measurements. Updates to the process include refinements to the tire sound quality synthesis process and to the regression model used to predict customer preference. These updates are based on the inclusion of additional data points representing a wide variety of tire designs.. Sound quality metrics are specifically developed for the tire noise application and used to improve the predicted subjective ratings of the synthesized in-vehicle noise predictions.

1. INTRODUCTION

Automotive tire noise is typically evaluated through subjective in-vehicle testing. This method has many drawbacks including person-to-person differences, the results being specific to a particular vehicle, time necessary to complete the evaluation, and the necessity of a complete set of tires and an appropriate vehicle for evaluation. Of more use to tire manufacturers is a method to quantify the predicted tire noise from tire measurements at the component level. This component-level test can be designed to quantify the tire as a vibration and acoustic source which can be tracked from the component level to the vehicle level as a predicted sound at the interior of a vehicle.

Initial process development was conducted on a sample size of eight tire designs and mainly concentrated on the airborne contributions of the tire noise signal. Recent process developments have allowed for the addition of an improved model for the structure-borne contributions to the predicted sound as well as the inclusion of many additional tire designs. Other process improvements include the definition of global masking models that can be applied to the synthesized sounds to replace the tire-specific masking models previously developed, and the optimization of the regression model used to predict the subjective ratings. The initial regression model, which was based on the original set of eight tires, has been updated to capture the unique characteristics of the additional tire designs evaluated.

2. TIRE NOISE PREDICTION – INITIAL PROCESS DEVELOPMENT

A. Road Testing

Initial process developments for the tire noise prediction were based upon the evaluation of eight unique sets of tires on a mid-sized sedan. The vehicle utilized was chosen to be a representative sample of the population of vehicles in this category. Subjective ratings were conducted with each of the eight tire designs for use in correlation efforts later in the development process.

Objective noise and vibration measurements were conducted on a controlled road surface under various events, including light drive-up, coast-down, and constant speed tests. Instrumentation for all testing included a binaural head in the passenger's seat, two microphones at each tire, tri-axial accelerometers at each spindle, an engine tachometer, and a wheel encoder.

B. Jury Evaluation Testing

The data collected during on-road testing was used to the conduct a formal jury evaluation to correlate the subjective responses of the jury to the objective data collected. Forty-five jurors participated in the paired comparison test created to evaluate their preferences for the measured tire noise for both a coast-down and a cruise event.

C. Regression Model Development

Initial hypothesis were confirmed that the subjective responses could be predicted using metrics from three general categories:

1. Loudness: A measure of the overall sound level produced during the test
2. Spectral balance: How the mid-frequency content compares to low/high frequencies
3. Tonality: Presence of order related noise due to the tread pitch sequencing

Multiple metrics from each category were calculated from the eight measured sounds and regressed against the responses of the jury evaluation to develop a sound quality regression equation to predict subjective responses from the measured data. Figure 1 compares the subjective ratings from the jury evaluation (original merits) against the predicted ratings from the regression model.

$$\text{Subjective Rating} = -c_1[\text{Loudness Term}] + -c_2[\text{Spectral Balance Term}] + -c_3[\text{Tonality Term}]$$

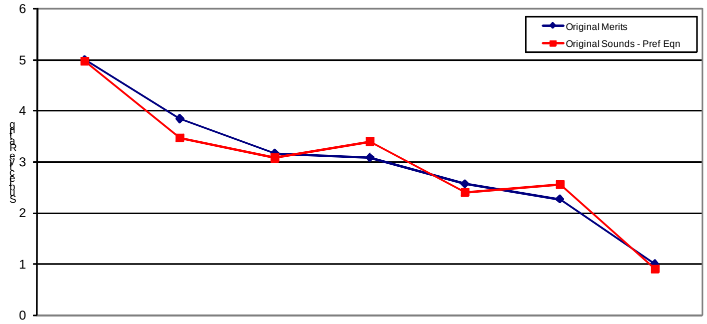

Figure 1: Jury Ratings Compared to Regression Model Prediction

D. Characterization of Sources and Paths

To begin the investigation to characterize the critical sources and paths for the tire noise, the mid-sized sedan was evaluated on a chassis dynamometer under similar conditions to the on-road evaluations. Steps were taken to verify that the contact patch between the tire and the dynamometer road was consistent with the contact patch with the road by comparing pressure spectra between the two surfaces.

Additionally the vehicle was evaluated on the chassis rolls with only one tire rolling at a time by removing the non-critical tire and supporting the vehicle weight with airbags. The vehicle ride height and tire contact patch were monitored to maintain consistency. This data was collected to measure the contribution from a single source, and was repeated at each of the four tire locations around the vehicle.

Characterization of the airborne paths was initially conducted via several different methods. These methods all measured the transmission loss from the tire patch to the vehicle interior using a broadband noise source. Partial coherence analysis of the operating data was used as the control in evaluating each of the possible methods, and ultimately used to select the proper method for this application. Structure-borne paths were measured by the sensitivity of sound due to force inputs at the vehicle spindles (P/F).

E. Component Level Test Development

A component level test stand was developed for this study specifically to use for noise and vibration measurements. The test stand allows for the characterization of a single tire as both an acoustic and a vibration source, to which the vehicle level transfer functions can be applied to predict the sound levels inside the vehicle.

F. Synthesis Process Development

The predicted sound levels for airborne contribution of tire noise can be summarized by the following:

$$SPL(tire)_{interior} = Tire(t) * NR_{vehicle}(f) \quad (1)$$

for: $Tire(t)$ = Interior sound pressure in the time domain, and

$NR_{vehicle}(f)$ = Noise reduction of vehicle from the tire patch(es) to the vehicle interior.

Utilizing this relationship, the sound pressure at the interior of the vehicle can be predicted from the tire noise measured from the component level test stand and the noise reduction transfer function from the tire patch to the vehicle interior. The interior sound prediction accounted for propagation from each of the four tires, including a phase relationship between each of the four corners.

Engine noise was accounted for through an engine masking term, which was measured during the on-road vehicle evaluations. Time-synchronous averaging was used to extract the components of the sound relating to the engine, such that is could be added to the predicted sound levels in the synthesis. A vehicle masking term was included that accounted for all sounds not related to the engine or the tires. This term was developed from the on-road testing, and added to the predicted sound levels in the synthesis. Using this method, both the engine and vehicle masking terms were unique for each tire design evaluated for this study.

3. TIRE NOISE PREDICTION – PROCESS UPDATES

A. Evaluation of Additional Tire Designs

Initial development of the synthesis process and regression equation was completed using eight tire sets. Each tire set was composed of unique design elements that had an impact on the noise and vibration signatures generated, and thus created unique impressions during vehicle evaluations. The selection of these particular tires was intentional to cover a wide variety of design elements, however in no way were these eight able to capture the full spectrum of design elements possible for all tires.

With continued development and refinement of this process, many additional tires and tire designs have been evaluated. Each of these designs created individual noise and vibrations characteristics that the synthesis process and regression equation were responsible for characterizing. With the inclusion of more data points, it became obvious that both the synthesis process and regression equation could be further optimized, either for improved predictions or for reduced time and efforts. To date approximately 30 tire designs have been evaluated for this model. The process improvements developed based upon these additional samples are described in the following sections.

B. Structure-borne Contributions

The synthesis process was initially developed with a concentration mainly on the airborne contributions for tire noise. Process improvements were necessary to include the structure-borne contributions, which are significant primarily for lower frequencies. To characterize the structure-borne energy generated by the tire, vibrations measurements were added to the component level test stand in a similar position to the vehicle spindle measurements. These measurements, in combination with vehicle level sensitivity measurements and transfer functions developed between the test stand and the vehicle spindle, were then used to predict the acoustic responses inside the vehicle due to the structure-borne contributions.

It was confirmed through detailed analysis of the predicted and measured sound pressure levels that the structure-borne contributions were significant in the lower frequency ranges and the higher frequencies were dominated by the airborne contributions. To accommodate these differences within the synthesis process, a low-pass filter was applied to the structure-borne contributions and a high-pass filter was applied to the airborne contributions prior to combinations within the model.

C. Generalized Masking Model Development

Within the synthesis process two masking models were developed to account for a) engine noise, and b) all other vehicle related sounds not associated with either tire noise or engine noise. Initial development of these models was based from on-road vehicle level data. Synchronous time averaging was used to extract the components of the sound related to the engine, yielding the engine masking term. The vehicle masking term was developed similarly through removal of both the engine and tire contributions from the on-road collected data, with the remainder being the vehicle masking.

Both of these terms, the engine masking and vehicle masking, were initially related to a specific on-road measurement. The need was identified to develop generalized masking terms that could be applied to all future synthesized sounds to eliminate the need for on-road measurements.

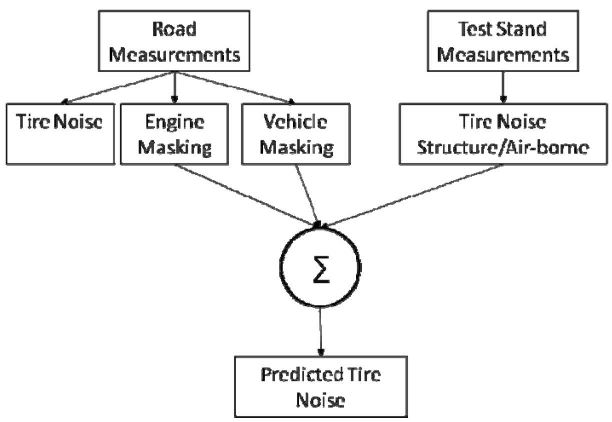

Figure 2: Synthesis Flow-chart – Original Process

The generalized engine masking development began with a comparison of all of the individual engine masking terms from the on-road collected vehicle data. As expected, the engine noises extracted from each individual measurement were relatively similar. The generalized engine masking term was then created as an average of all of the individual masking terms.

The generalized vehicle masking term development was more complex. Each of the individual vehicle masking terms extracted from the on-road data was generated through removal of the engine and tire noise via synchronous time averaging. With this method, the tire noise extracted from the on-road signal was only the content that was synchronous with the tire rotation speed. Resonances of the tire which are constant frequency based, and not synchronous to the tire, were not extracted as "tire noise" with this method, but rather remained as part of the vehicle masking term. This required additional attention to ensure proper development of the generalized vehicle masking term, as well for accurate predictions within the synthesis process.

Each of the tire designs evaluated for the initial process development contained different design elements that produced different resonances that made up the acoustic signature. Because of this, a comparison of all of the vehicle masking terms from the on-road data yielded much more variation than initially expected. The generalized vehicle masking term, which was eventually developed as a combination of all of the individual vehicle masking terms, contained pieces of all of the resonance frequencies from all of the tire designs evaluated. The results was a generalized term that tended to be less tonal than the individual terms, however still provided the appropriate content to accurately represent the vehicle level masking for future tire noise synthesis development.

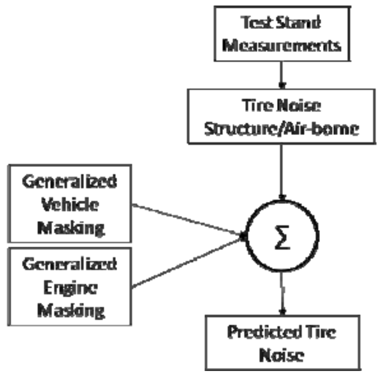

Figure 3: Synthesis Flow-chart – Updated Process

D. Regression Model Updates

The regression model is used to predict the customer preference (subjective ranking) for tire noise, and is based solely on objective data. This data can either be actual in-vehicle measurements or, more importantly, predicted sound pressure levels from the synthesis process. The regression model developed from the original set of eight tires was based on three categories of sound quality metrics including a loudness term, a spectral balance term, and a tonality term. With the evaluation of additional tire designs it became obvious that the regression equation could be refined to improve predictions for a wider variety of tire designs.

The regression model refinement began with a review of the sound pressure levels and narrowband data for all of the tire designs evaluated to listen and look for similarities and differences. Observations included the presence of tonality variations at lower frequencies likely due to tire cavity modes, as well as the presence of a distinct tire-band frequency range in the low-to-mid frequency range.

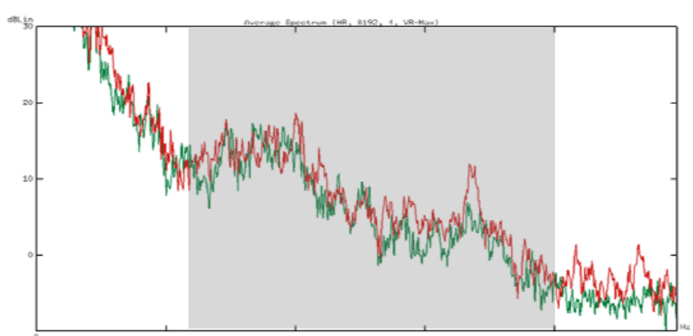

Figure 4: Tire-band Frequency Range

The tonality category in the regression equation used a global metric that was calculated over the entire spectrum. It was determined that by band-passing the signal into key frequency ranges and calculating metrics separately, improvements would be seen in the model. The spectral balance term was refined similarly with the identification of key frequency ranges that significantly impacted the customers' perception of tire noise.

The resulting refinement of the regression equation provided an improved prediction of customer preference, the result of which can be seen in Figure 5.

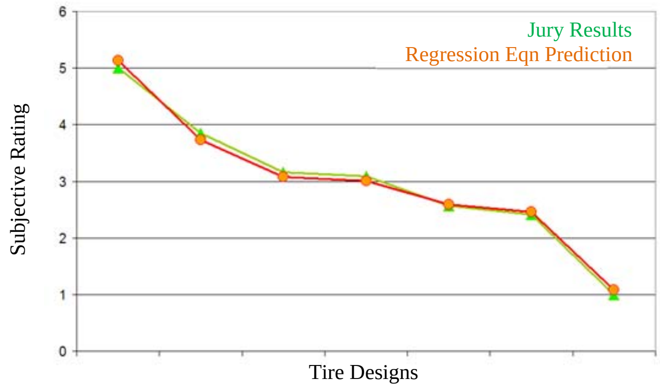

Figure 5: Jury Ratings Compared to Refined Regression Model Predictions

4. SUMMARY

The tire sound quality prediction process has proven to be a highly useful method for evaluating automotive tire noise. The process allows for the prediction of vehicle-level interior noise based solely on component level test stand measurements from a single tire.

Throughout the process development, steps have been made to continue to improve the quality of the process and to minimize the required time and efforts to use it. Major process improvements have included the measurement and synthesis of many additional tire designs, the improvement of the acoustic predictions due to structure-borne contributions, the development of generalized masking terms, and improvements to the regression model used to predict customer preference. All of these steps have yielded improved predictions for both interior sound levels and subjective ratings, providing a method for performing tire noise evaluations without the time and resources required for full vehicle evaluations.

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