TINO

BRITE EURAM PROJECT BRPR – CT95 – 0121

1° INTERNATIONAL COLLOQUIUM ON VEHICLE TYRE ROAD INTERACTION
"THE NOISE EMISSION"

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TINO Noise Emission: Analysis and Prediction Models

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ABSTRACT

The purpose of this paper is to present the numerical methodologies to analyse and predict tyre noise emission that were developed within the framework of the TINO project. In order to analyse the tyre noise source, numerical acoustic holography techniques have been developed on basis of the inverse boundary element method and experimentally validated. A methodology for predicting the noise emitted by a rolling tyre has been implemented, by combining a structural transient finite element approach with a radiation model based on an acoustic infinite element technology.

INTRODUCTION

The noise emitted by the tyres of a car cruising at a medium to high speed is an extremely important contributor to the total radiated noise. Since government regulations are becoming ever more strict on allowed pass-by noise levels, it becomes critical to implement computer-aided engineering (CAE) techniques that allows to analyse and to predict the structural-acoustic characteristics of rolling tyres. Such techniques are thus the corner stone of an optimised process, where the noise characteristics of new tyres can be assessed on a virtual prototype, and refined very early in the design and development cycle, even before any physical prototypes can be tested.

The purpose of this paper is to present the numerical methodologies to analyse and predict tyre noise emission that were developed within the framework of the BRITE EURAM TINO project.

In order to analyse the tyre noise source, a numerical acoustic holography technique has been developed on basis of the SYSNOISE direct boundary element method (D-BEM) and experimentally validated.

A methodology for predicting the noise emitted by a rolling tyre has been implemented, by combining a structural transient finite element approach (ABAQUS) with a radiation model based on an acoustic infinite element technology (SYSNOISE). Some very specific modelling issues have been addressed, such as:

- Convert vibration data from a rolling tyre (rotating structural mesh) to a vibrating but static model (fixed acoustic mesh);
- Create the acoustic mesh for supporting the infinite element modelling;
- Take into account the road surface impedance.

NUMERICAL ACOUSTIC HOLOGRAPHY

An important task in the TINO project aimed at developing an inverse method for the determination of the surface vibration velocities, based on acoustic measurements in the vicinity of the tire. The technique, being essentially a source identification method, makes use of numerically calculated transfer functions between the radiating (i.e. source) and sensing (also called measurement or holography) surface and as such, can be considered as a generalisation of the near-field acoustic holography (NAH) method. Unlike NAH though, it is not burdened by the limitation that both the source and the measurement surface must be plane or of some other elementary shape - which is a vital asset from the tyre analyst's point of view. Its close relationship with the Boundary Element Method implies that it is more correct to denote it as an inverse BE method (inverse BEM).

It is also wroth noting that inverse BEM and ASQ (Airborne Source Quantification) are closely related as well, with the essential difference that the transfer matrix is determined for the inverse BEM numerically rather than experimentally. As one can expect, so are the problems and inaccuracies of both methods too.

THEORETICAL BACKGROUND

As mentioned, the technique is based on the direct BEM (SYSNOISE). Starting from Helmholtz equation, the governing equation of the radiation problem of a general vibrating surface can be described in its discrete form as:

$$[A]\{p_s(x)\} - [B]\{v_s(x)\} = \{p(y)\} \qquad (1)$$

relating the surface sound pressure p_S and surface normal particle velocity v_S in any arbitrary node *x* along the source surface mesh to any arbitrary point *y* outside of the surface through the influence matrices [*A*] and [*B*].

The problem can be solved in two consecutive steps. At first, one assumes that point *y* is selected onto the source surface. Then Equation (1) becomes

$$[A]\{p_s\} = [B]\{v_s\} \qquad (2)$$

and the resulting system of equation can be solved, provided that either surface pressures or surface velocities are known as prescribed boundary conditions for any arbitrary node.

Secondly, if point y is selected in the acoustic region, the resulting radiated pressure p_r can be obtained from

$$[a]\{p_s\} + [b]\{v_s\} = \{p_r\} \qquad (3)$$

where the matrices $[a]$ and $[b]$ describe the participation of the various nodes in the radiated field and can therefore be referred to as contribution matrices.

The inversion of the calculation can easily be deduced from Equations (2) and (3):

$$\{p_m\} = \left[[a][A]^{-1}[B] + [b]\right]\{v_s\} = [c]\{v_s\} \qquad (4)$$

and then

$$\{v_s\} = [c]^{-1}\{p_m\} \qquad (5)$$

where p_m stands for the measured pressure, determined along measurement points of an arbitrary measurement surface. The matrix [*c*] can be denoted as the transfer matrix of the system and $\{v_s\}$ is the vector of sought surface velocities.

The solution of Equation (4) in principle rather straightforward, provided that the number of microphone positions along the measurement surface is greater than, or at least equal to, the number of elements on the source surface, and that matrix [*c*] is not singular.

EXPERIMENTAL VALIDATION

After having validated the method on small testing objects, the procedure was applied to the tyre noise problem. First a wooden tyre mock-up with six built-in, independent loudspeakers was constructed (see figure 1), and calibrated by means of a laser Doppler vibrometer. The experiments have resulted in good qualitative (see figure 2) and quantitative surface velocity distribution, provided that the source model and the measurement point mesh surface is appropriately matched. If this is not the case, the matrix to be inverted is badly conditioned and poor results can only be obtained, even if sophisticated matrix regularisation methods are used.

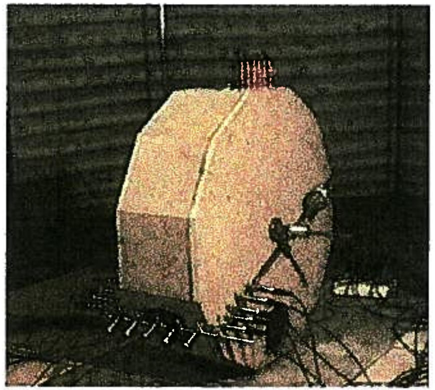

Figure 1: Experimental set-up (wooden tyre mock-up)

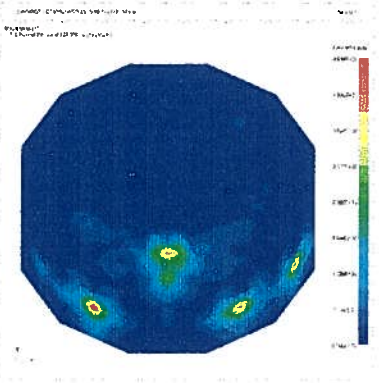

Figure 2: reconstructed surface velocity distribution

The results were applied on real-life measurements too. A numerical model of a Pirelli tyre was developed and the transfer matrix was calculated by means of a combined SYSNOISE/MATLAB calculation procedure. Operational sound pressure data, measured in the anechoic chamber of Pirelli originally performed for ASQ investigations, were used as input and the surface velocities calculated. A typical source distribution is shown in figure 3.

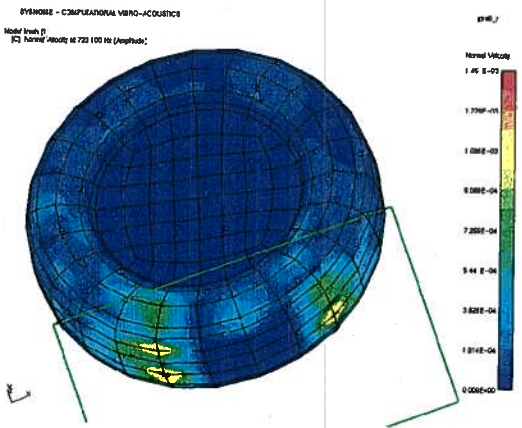

Figure 3: Reconstructed source distribution on a real-life tyre.

Even though no direct surface velocities are available for verification purposes, the calculated source distribution can be checked indirectly by recalculating the radiated sound field along another surface and comparing it to measured data. It was shown that the agreement is somewhat poor for low frequencies but improves and becomes rather good for higher frequencies.

RESULT DISCUSSION

It appears that the inverse boundary element method (inverse BEM) is a viable alternative to near-field acoustic holography (NAH) and airborne source quantification (ASQ). Its advantage with respect to NAH is that the applied mesh surfaces can be of arbitrary shape, and inverse BEM usually takes less effort than ASQ. On the other hand, the accuracy of the results depends on frequency: the obtained results are more accurate for higher than for lower frequencies. This effect is very likely due to the condition number of the matrix defining the inverse problem (see Equations 4 and 5). The inverse BEM also requires a well-matched source and measurement surface mesh and mostly some mathematical matrix regularisation methods.

PREDICTIVE STRUCTURAL-ACOUSTIC METHODOLOGY

Complementary to the analysis method developed above, based on an inverse boundary element technique, for identifying the noise sources, the TINO consortium developed a predictive methodology for allowing predicting and optimising the acoustic performance of tyres, based on virtual prototypes.

The developed methodology consists of three steps:

- Build a structural finite element model, using ABAQUS, allowing to determine the tyre structural vibrations, in the time domain;
- A new tool to transfer vibration data from the ABAQUS structural model onto the SYSNOISE acoustic model;
- Build an acoustic model, using SYSNOISE, based on a mixed finite and infinite element technology.

STRUCTURAL MODEL

The structural dynamic model of the rolling tyre is created using the ABAQUS/Explicit program. The tyre can be modelled as slick or with a tread pattern. The tread pattern can be represented on a limited angular sector of the whole tyre depending on the total time period to be simulated (see figure 4).

A 3 dimensional model made of continuous solid elements is built representing the unloaded tyre mounted on the rim. The tyre is then inflated, vertically deflected, and rotated over a time period of 100 milliseconds at a constant speed, either on a smooth surface, or on a surface with a cleat. The cleat can be seen as an obstacle exciting the tyre structure similarly to the road roughness. Contact friction is included in the simulation in terms of Coulomb constant friction coefficient.

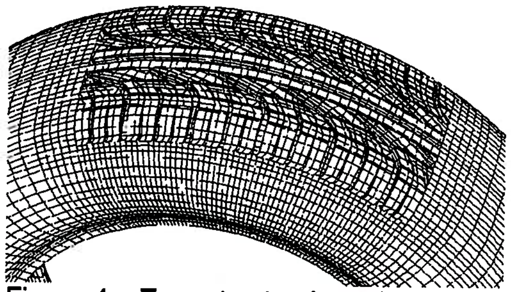

Figure 4: Tyre structural mesh of the tyre with tread pattern in a limited angular sector

Tread blocks can be meshed with a different number of finite elements in length, width and depth. As a consequence nodes on the outer tyre surface can be in contact with the drum surface and/or with each other, and nodes belonging to the geometry of the tread grooves but not to the outer surface can be in contact with each other when the grooves deform.

The deformed geometry (nodal cartesian co-ordinates) are monitored as a function of the time. A rotated and deformed mesh is then created at each time step.

CREATION OF THE ACOUSTIC MODEL

After investigation of various solution methodologies, the acoustic finite element method, combined with infinite elements for taking into account the free field radiation (Sommerfeld condition), has been selected to support the acoustic radiation model.

A methodology has been developed in Pre/SYSNOISE to automate the generation of the conventional finite element mesh, representing the near-field region between the tyre surface and the outer surface where the infinite elements are attached. Because of symmetry reason, half of the model is meshed. The model creation procedure is shown at figure 5.

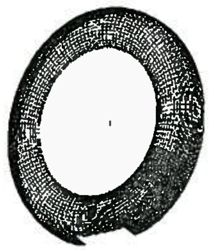

Figure 5.a: Half of the tyre structural mesh

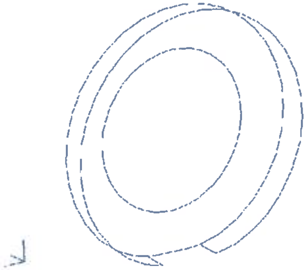

Figure 5.b: Creation of the tyre geometry surfaces (Pre/SYSNOISE)

Figure 5.c: Creation of the outer surface, where infinite elements will be attached.

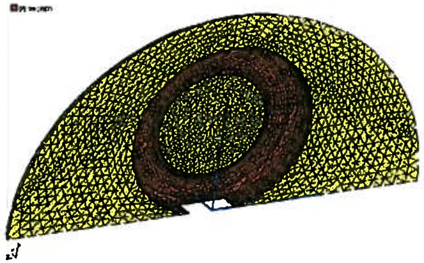

Figure 5.d: Creation of the volume element mesh in the near field. The red coloured faces represent the tyre surface (vibration boundary conditions).

VIBRATION RESULT TRANSFER ONTO THE ACOUSTIC MODEL

The noise sources are represented in the acoustic model by vibration boundary conditions, applied as transient accelerations on the tyre surface (red surface of figure 5.d). It should be noted that the nodes of the acoustic model are not coinciding with the nodes of the structural model. Moreover, the structural mesh is rotating while the acoustic mesh is fixed in space during the time integration (with time varying vibration conditions). For these reasons, a specific methodology has been developed to convert the ABAQUS structural results into correct SYSNOISE acceleration boundary conditions.

The normal acceleration boundary conditions are obtained in three steps:

- The structural accelerations are calculated onto the structural mesh using the finite difference method (specific Fortran program);
- The acceleration data are projected onto the acoustic mesh nodes (procedure TRANSFER);
- The time dependent acceleration boundary conditions are created on faces of acoustic finite elements and stored in the SYSNOISE model database (procedure GENERATE).

ACOUSTIC MODEL

The acoustic model is based on a combined finite/infinite element method. The method selected, allowing transient analysis, is based on a conjugated formulation, sometimes called the wave envelope element technology (see figure 6).

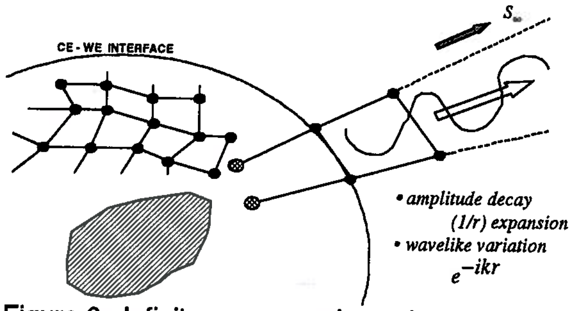

Figure 6: Infinite wave envelope element

The infinite wave envelope element is based on a geometry mapping extending the element to infinity. The element shape functions have a built-in amplitude decay

(1/r) and a wave-like variation (e^{-ikr}). The element is called conjugated because the weighting function is the complex conjugate of the shape function.

The finite/infinite element method present several advantages for tyre radiated noise prediction:

- Supports an efficient transient analysis solution sequence, using sparse matrix arithmetic;
- Allows to take into account the road surface impedance in the region near the tyre;
- Is less sensitive to modelling errors as the boundary element method, and is not sensitive to irregular frequencies related to internal cavity resonance;
- Allows far field point post-processing;
- Supports extensions such as taking into account the air flow, and coupling with the internal tyre cavity;

The figure 7 represents the acoustic sound pressure levels within the conventional acoustic finite element region at time t=0.108 milliseconds. The red areas correspond to the region that is not yet reached by the acoustic waves. The figure 8 represents the acoustic sound pressure distribution on a virtual exterior surface. This surface consists of field points within the infinite element region, and is used for visualisation only.

Figure 7: Distribution of pressure at time : t =0.108 ms

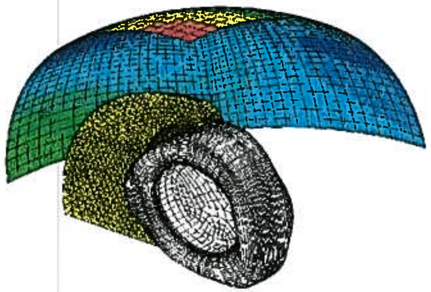

Figure 8: Field point post-processing in the infinite element region

CONCLUSION

Numerical procedures have been presented that allows:

- To analyse and identify the tyre noise sources, based on an inverse boundary element method. This procedure allows to determine the surface vibration velocities starting from acoustic field measurements. The results of the experimental validation indicate that the mathematical process is more stable at higher frequencies, and that the location of the measurement points with respect to the surface boundary nodes needs to be carefully selected;
- To predict the structural dynamic behaviour of tyres and their acoustic radiation, based on transient structural finite element analysis and on an acoustic finite/infinite element method. This technique is the basis of a refinement methodology allowing one to design better tyres, since it gives the possibility to assess the vibro-acoustic performance even before hard prototypes can be built.

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