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TITLE : AQUSTA
Improvement of the structural Acoustic Qua ity of transportation vehicles Using Simulation Techniques of binaural Analysis

PROJECT COORDINATOR : PSA PEUGEOT CITROEN

PARTNERS : SAINT GOBAIN VITRAGE
HEAD ACOUSTICS
HEAD CONSULT

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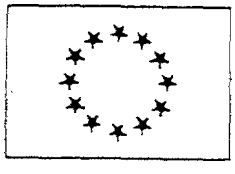

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1. Title

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3. Consortium description

Partner 1. PSA PEUGEOT CITROEN (Prime proposer, project co-ordinator)

PSA PEUGEOT CITROEN is sharply focused on the design, manufacture and marketing of automobiles, a business that accounts for 95 percent of consolidated sales. PSA PEUGEOT CITROEN encompasses two car companies, automobiles PEUGEOT and automobiles CITROEN. These companies benefit from a wide range of industrial, technological and financial synergy, which together, make them the third automobile manufacturers in Europe. However, each company retains its own mark identity, personality and marketing momentum. 1.986.800 vehicles have been produced world-wide in 1994.

The automobile division of PSA PEUGEOT CITROEN contains 4 divisions working for automobiles PEUGEOT and CITROEN: Research and Scientific Affairs, Information Technologies, Automotive Development and Technology, Industrial Methods and Equipment. Automobiles PEUGEOT sales: 10 1;8 billion francs in 1994, 69200 employees, world-wide production 1.202.000 vehicles. Automobile CITROEN sales: 70.7 billion francs in 1994, employees 45700, world wide production 784.800 vehicles. PSA PEUGEOT CITROEN's research division is dedicated to medium and long term applied research, design to integrate new and emerging technology into future automobile projects. A large proposition of these prograrnmes are concerned with environmental protection.

Partner 2. HEAD ACOUSTICS GmbH / HEAD CONSULT

HEAD ACOUSTICS is a Company engaged in subjective acoustic analysis. The major concern is the commercialisation of binaural measurement equipment with adequate binaural evaluation software and the research of developing advanced components and systems for recording and analysis of preferably binaural acoustic data. An autonomous subdivision, HEAD CONSULT, is involved in consulting and experimental noise and vibration analysis.

HEAD ACOUSTICS GmbH of D-Herzogenrath is a young and successful SME with great technical experience and capabilities regarding the binaural technology and subjective noise analysis, Since its foundation in 1986, HEAD has been engaged in implementing and using binaural technology. A major produc, which is successfully marketed worldwide, concerns binaural measurement technology, based on the company's artificial head measurement systems, the Aachen HEAD, plus adequate complex binaural evaluation software, the BAS-system.

HEAD with a staff of about 60 in Germany, has dealers under contract in USA, Japan, France, Italy and Great Britain. Available resources include Research and Development (R&D) as well as manufacturing facilities for hard and software. Main R&D activities refer to components and systems for recording and analysis of preferably binaural acoustic data.

Partner 3. **SAINT GOBAIN VITRAGE INTERNATIONAL**

SAINT GOBAIN is a French world leader in engineering materials based on glass, cast iron, fibres, ceramic, wood.

The main activity of the group is focused on the glass production in terms of elements for buildings. It is the first European and second world producer of elements for building and vehicles. The manufacture transforms and markets flat glass in Europe and has significant holding in four others, in Italy, in Brazil, and in Argentina. Emerging sectors are speciality glass for optics, electrodomestic appliances, aeronautics and electronics.

Sekurit Saint Gobain International: flat glasing department of Saint Gobain dedicated to the automotive industry, 20 countries, 7.000 employees, 600 searchers (R&D), 50% of the european market, 20% of mondial market.

2. Executive summary

1. Key words

Binaural simulation - structural acoustic modelling- design modification - vibration analysis - sound quality - signal processing - automotive

2. Abstract

Objectives

The objectives of this project was to build a prototype of an industrial tool dedicated to the subjective sound quality analysis.

Conventional Binaural Acoustic recording and analysis techniques were well-known for acoustic diagnosis in automotive industry. These techniques were based on a binaural dummy head recording system, and signal analysis system. Binaural acoustic response modifications were mainly based on signal processing techniques but not on physical models of the vehicle. These tools and techniques were mainly used to assist the acoustical engineer in diagnosis analysis in development process.

A new system has been developed and a prototype realised in this project

The new tool allows to build acoustic quality targets by simulation of realistic binaural acoustic responses based on physically realisable design modifications. These are obtained by signal modifications of recording measured on vehicle benches or in running conditions. These modifications are now done using a physical model of vehicle including multiple acoustical and mechanical sources, structureborne and airborne paths and binaural receiver. Methodologies and hypothesis to truncate paths to isolate *one* component has been defined and allow to modified the transfer characteristic of the component in several situations.

The transfer characteristic could be based on measurement data, numerical or analytical models. A great amount of this research work has been dedicated to define the hypothesis necessary to truncate the model to isolate one component in order to modify it. Here, the combination of binaural - multi-channels recording and simulation technique ("hybrid model") means the main innovative impact which allows a significant reduction of loops to design and test the object under design of modification process.

Direct and Inverse Methods have been developed to build the binaural acoustic model of vehicle in running conditions. Sources and Transfer paths can be measured and modified according to the hypothesis of decoupling. The direct method has been implemented in the new prototype.

Airborne path methodology has been developed in order to design modifications of the panels surrounding the cockpit. This method is based on acoustic transmission loss modification of the modified airborne path. Measured or calculated Transmission loss of individual panels (g-king) and insulation floor modification have been intensively developed and used for binaural simulation of aerodynamic noise effects.

The hardware and software of the binaural tool has been developed and tested by car manufacturer and supplier, The first prototype has been judged very promising. Several methods tested and developed in the project could be integrated in a future improved binaural / multi-channel recording and simulation system. New psycho-acoustic criteria based on a new human hearing model has been proposed and tested successfully.

The fields of application of such tool can clearly be enlarged at all the transportation systems and several other industrial sectors like environmental external acoustic and building construction.

3. Introduction

Transportation vehicle development cycle must still be reduced due to competitions. The main reduction will be obtained by the development of new design methodologies. In the past, and still today, development process in acoustic engineering consists in several loops with measurements, analysis, modification and verification on prototype. This procedure is time - and cost consuming -. In order to satisfy EEC Regulation and customers requirements, the acoustic comfort needs to be targeted and designed for each typical driving conditions. Validated vehicle acoustic design numerical tools are still under development and won't be available to calculate each typical driving conditions for several ten years. "Hybrid models" of acoustical vehicle behaviour must be developed. These "hybrid vehicles" will be based on a combination of measured and calculated data. These models will be used to build acoustic quality targets and to design modifications. The simulation and the listening of the binaural acoustic responses of vehicles will be based on the combination of experimental data of previous vehicle and design modifications of components using experimental or numerical data basis. Furthermore, binaural records (objective data) and judgments of the clients or experts (subjective data) must be correlated.

A new prototype of an industrial tool has been developed and realised in the project. It is dedicated to the subjective sound quality analysis of vehicle design modifications.

In a first part we present the research work to build the binaural multi-input multi-output structural acoustic model of vehicle. In a second part, the main hypothesis and methodologies developed to truncate or modify transfer paths and sources using numerical or experimental data are presented. The new hearing model is defined in the third part, Part four is dedicated to the prototype description and the tests in industrial environment.

4. Technical description

1. Binaural multi-input multi-output structural acoustic model of vehicle

The method and prototype developed allow to create an "hybrid model" of structural acoustic behaviour of vehicle.

The binaural acoustic response recorded in the vehicle with dummy head can be mathematically define as the sum of the contributions of several mechanical and acoustical sources propagating waves which impact head, The objective of the project was to build this model including equivalent mechanical and acoustical forces, structure borne and airborne transfer paths. Two methods have been developed to establish the model. The Direct Method and the Inverse Method. In a preliminary stage, it is necessary for the both methods to create a good physical model of the vehicle in order to define the best location of the point measurements used to estimate equivalent forces and transfer paths. Transfer path measurement have been investigated in a wide frequency range using, direct or reciprocal methods with dedicated developed sources according to the frequency range and the nature of the sources (forces or acoustical volume velocity).
The Direct method is based on direct measurement of the forces in running conditions at the connecting points using stiffness matrix approach for the connecting mounts and impedance matrix for the structure to be connected. The figure 1 provide an illustration of the model for an engine connected to the body structure with three engine mount.

The Inverse Method is based on the simultaneous measurement of the acceleration or pressure at several locations on the body structure or in air in running condition. Then the transfer path matrix is used to determine the cross-spectrum matrix of the equivalent mechanical forces or acoustic forces in running condition. Reference signals are used when several physical dynamic behaviors are responsible of the primary feces generation. With these reference signals, virtual spectra can be calculated and used for the global model. A flow chart of the method is presented on figure 2.

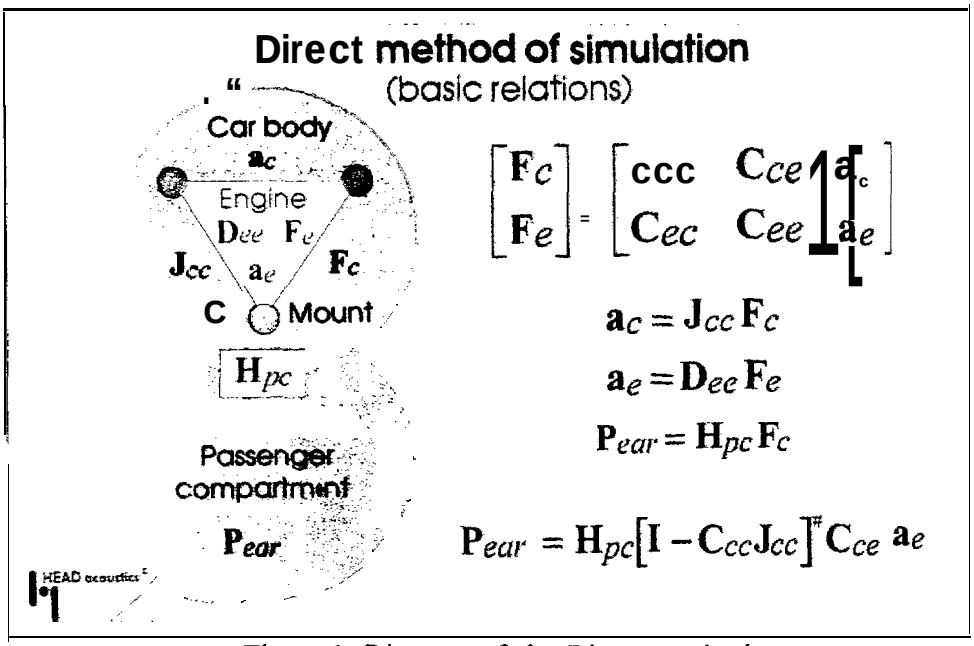

Figure 1: Diagram of the Direct Method

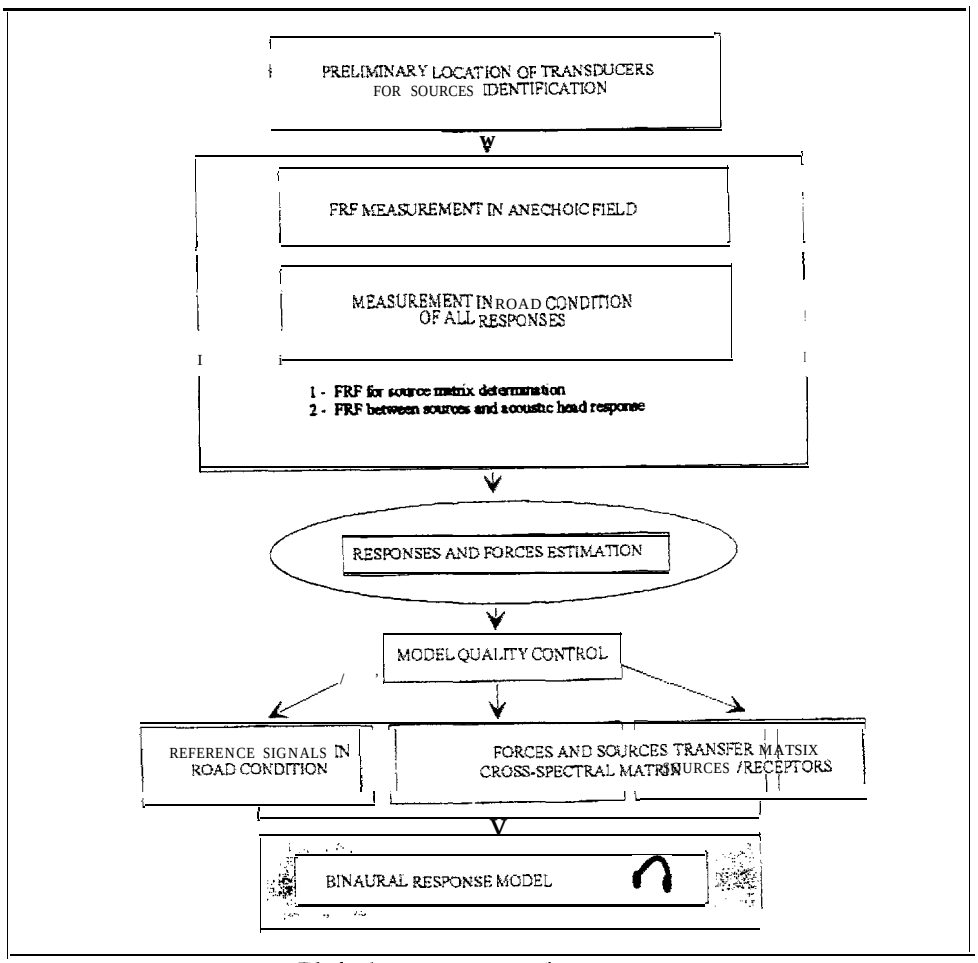

Figure 2: Global Flow Shart of the Inverse Method

One example of the comparison of the pressure measured in the passenger compartment calculated with the inverse method is presented cm figure 3. With these models and signals recorded during the test, the noise inside the passenger compartment can be listen using convolution technique. The quality of the results depends of the location of the sensors used for equivalent sources calculations and of the quality of the transfer function measurements. A lot of work *has* been done to develop methodology allowing better optimisation of the sensor location.

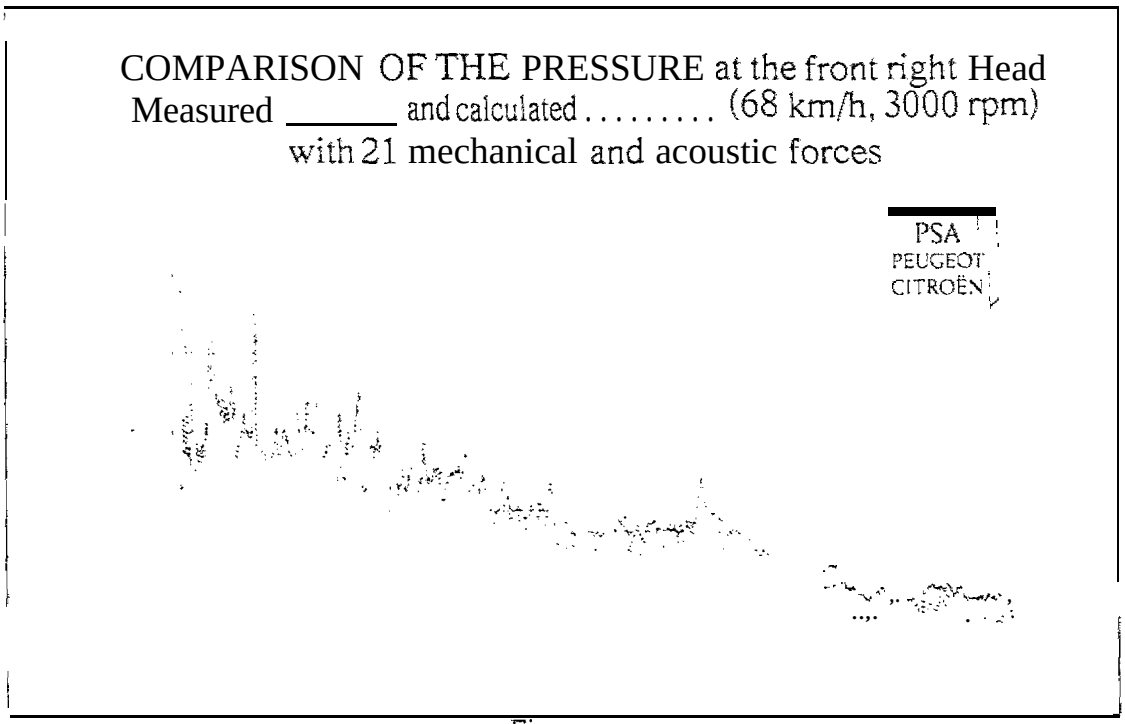

Figure 3

Investigation process was developed using holographic techniques and a measurement system (hardware, and software) was developed to determine acoustic equivalent sources and sensor location.

The two methods have been intensively investigated and the direct method is presently implemented in the prototype tool.

2. **Simulation modification**

- Methodology

The "hybrid model" developed and presented in part 4.1 is basically created with experimental data in order to obtain realistic binaural responses covering the wide frequency range of human hearing. Then one has to develop methodology and hypothesis to modify the source terms and the transfer paths with new data based on other experiments on numerical or analytical simulation of modified components.

Theoretical work on structural-acoustic coupling effect was conducted using experiments and finite element and boundary element calculations to investigate the frequency domain of application of low coupling hypothesis. Both coupling between several mechanical substructure and internal and external acoustic field have been studied. It allows to define several approaches depending of the component to be modified and the frequency domain.

- Structure borne path

Simulation modification of structure borne path was mainly focused on resilient mount modification. Several dedicated benches were developed by HEAD CONSULT and PSA to provide the engine mount matrix blox. Direct listening of modification of structure borne path was developed and tested by HEAD CONSULT and included in the prototype system by HEAD ACOUSTICS. The 'system works in stationary conditions and with engine speed variation. In the future variable engine mount matrix bloc must be included to take in account variation of load conditions. Several test with engine mount disconnected and modified were conduced by HEAD ACOUSTICS.

- Airborne path

Detail work has been conduced on airborne transfer path mechanism in order to truncate the transfer path and isolate the contribution of each panel surrounding the cockpit for each airborne acoustic source. Modification in the recording strategy is sometimes necessary to isolate each individual contribution.

A strategy to define equivalent acoustic volume velocity sources have been developed to locate these equivalent source using acoustic holography and inverse techniques. These techniques were tested on powertrain in anechoïc chamber and rolling noise at rolling bench.

Two methods to truncate the airborne path were developed and one of them was tested and validated on simulation of glazing coincidence effect of CITROEN ZXS lateral glasses in aerodynamic wind tunnel with prototype modification to correlate the results.

Acoustic aerodynamic noise contribution of individual panel on CITROEN 2X vehicle has been used to test the method. The measurement was conduced by PSA and Saint-Gobain in BMW aerodynamic wind tunnel in Munich at different speeds with several conditions of the insulation.

- Transmission loss measurement and modelling

The transmission loss of panels surrounding the cockpit of the ZX car have been tested (roof, floor, doors , windscreen, lateral glasses,.) with updated intensity measurement technique allowing individual sub-panel transmission loss measurement. Basic components were tested in the preliminary stage to validate the calculations models.

Advanced modelling of glasses were conducted by Saint Gobain using boundary and finite element new models in medium and high frequency These models can take in account multilayer glasses and glued boundary conditions. An exemple of con-elation on laminated windscreen of ZX car is provided on figure 4,

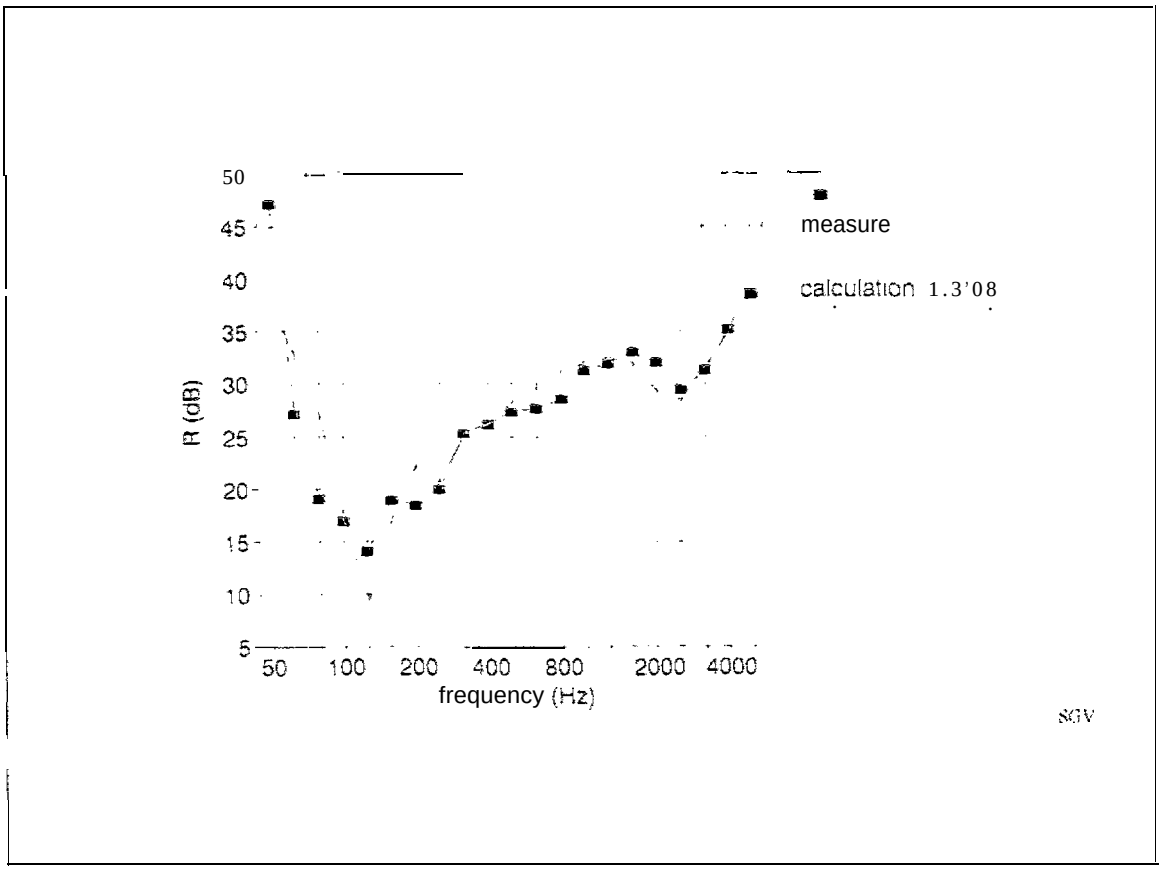

Figure 4: Transmission loss simulation of multilayer glasses

Dedicated models of transmission loss of complex panel to simulate transmission loss modification was developed by PSA to test floor insulation modifications.

- Simulation of panel modification.

The new method of binaural simulation was tested by PSA and Saint Gobain using modifications of lateral glasses of the front doors of ZX car in aerodynamic wind tunnel at 140 Km/h. Typical results are presented in figure 5

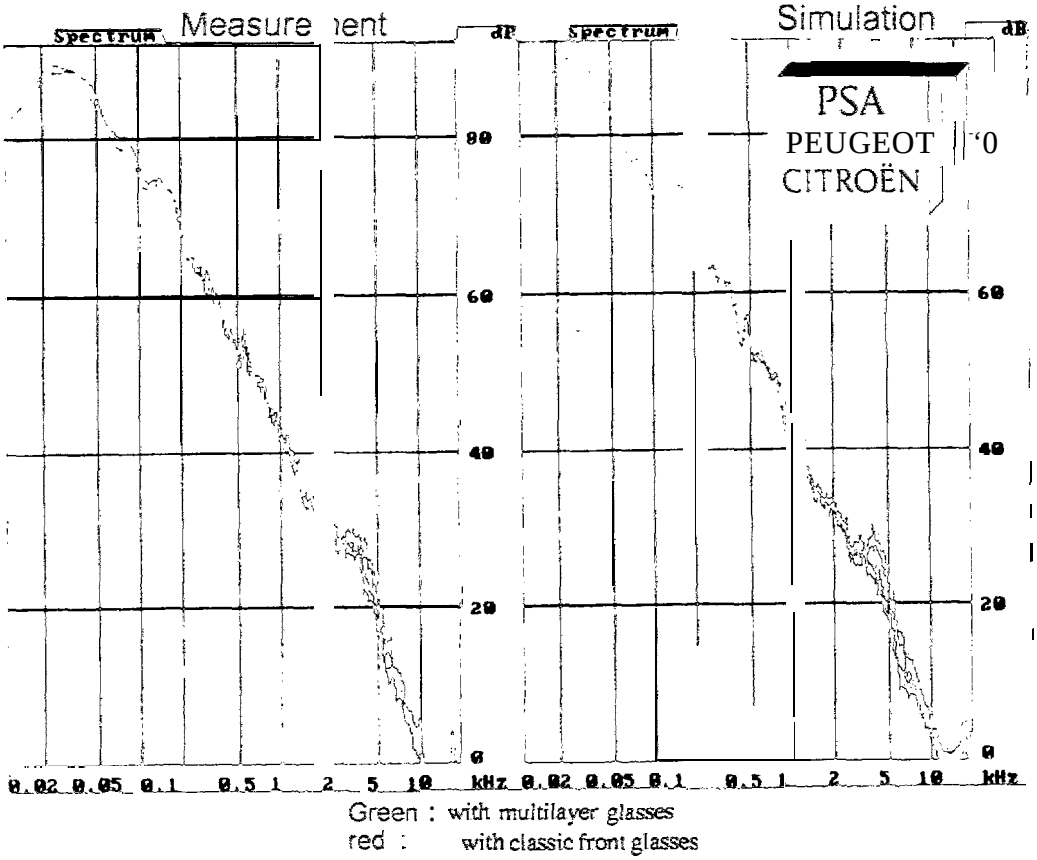

Figure 5: Comparison of measurement and simulation of front glass vehicle modification with aerodynamic noise on ZX car at 140 km/h

3. Hearing model

A new model of hearing human system was developed by Head Acoustic. This system which is closer to the human ear behaviour was used to analyse the acoustic noise of vehicle and to define new quality index.. Figure 6 presents the main features of t he system,

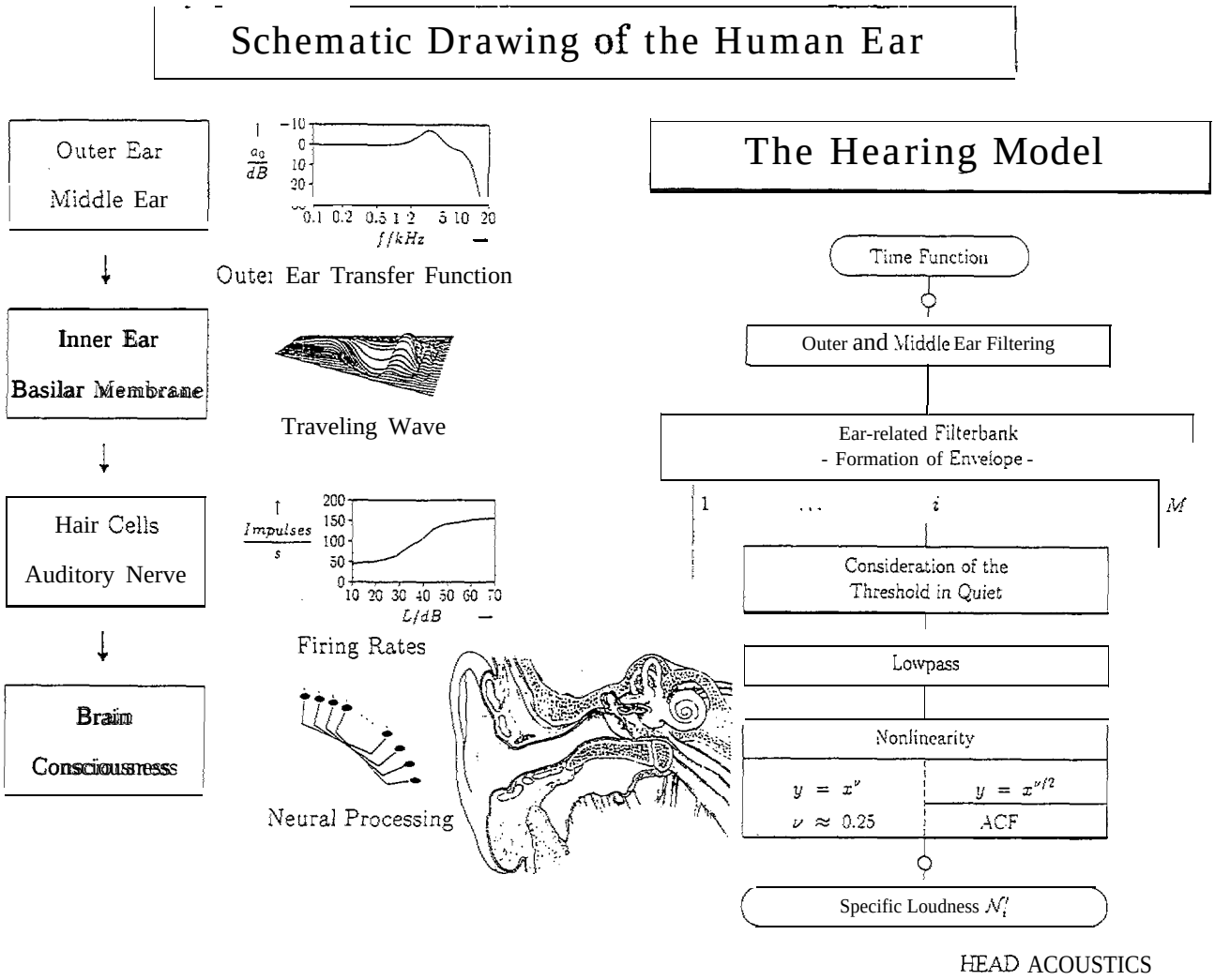

Figure 6

The binaural simulation was used to practise a test at PSA with several end users in order to verify the reliability of the simulation.

4. Prototype of industrial tool

Hardware and Software

A prototype of an industrial tool was realised by Head Acoustic based on measured binaural recordings and component modifications using simulation techniques. A new recording system used to record data in running conditions has been developed. The global flow chart of the system can be seen on figure 7.

The simulation software manages data basis of components which can be modified (transmission 10ss, stiffness matrix of resilient mount, transfer functions of transfer paths, equivalent spectrum of sources). These data basis can be linked with external main computer for advanced Boundary Element Method, or experimental data basis or analytical software. The system allows several post-treatment and direct listening of the binaural modifications.

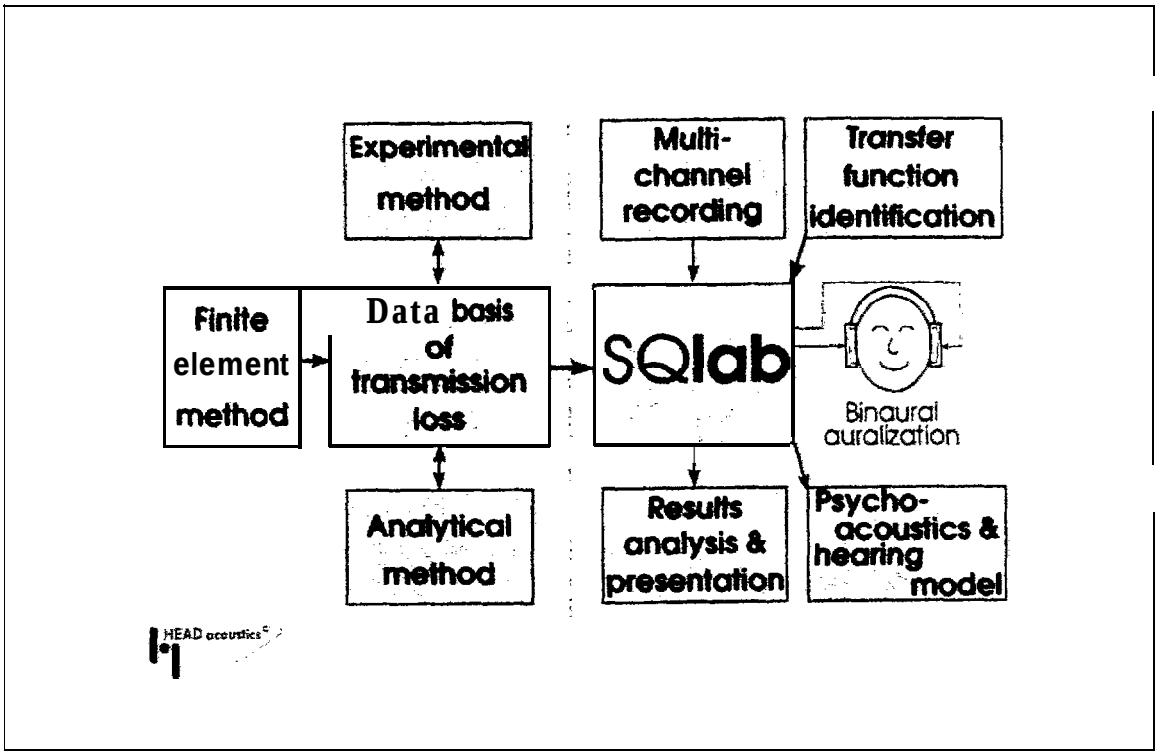

figure 7

-Test in industry

The prototype system was tested at Saint Gobain and PSA PEUGEOT CITROEN with the direct force method and transparency modification modules available. Tests were conducted satisfactory and suggestions to improve the system were transmitted to HEAD ACOUSTICS

5. Results

• Models : two binaural multi-input multi-output structural models of vehicle have been developed and tested on vehicle at rolling bench and in road conditions.
The Direct Method has been developed by HEAD ACOUSTICS.
The Inverse Method has been developed by PSA.

Softwares have been developed and the Direct Method has been filly implemented in the new prototype tool.
Great amount of tests on vehicle at rolling bench in running situation have been conducted by HEAD acoustics and PSA PEUGEOT CITROEN to develop and validate the methods.

• Design modifications and data basis

- engine mount dynamic characteristics have been tested on the basis on the development of dedicated dynamic benches developed by HEAD acoustics and PSA PEUGEOT CITROEN. These data are transferee to the data basis matrix blocs of the new tool to simulate modifications.

mechanical and acoustic sources have been tested and dedicated method like acoustic holography and inverse method have been developed to measure the acoustic volume velocity of equivalent sources (PSA).

- transmission loss calculation of simple and multilayer glasses glued on trimmed structure have been developed by SAINT GOBAIN VITRAGE. In the Low Frequency range, the <calculations are based on Boundary Element and Finite Element Models. In the Medium and High Frequency Range, the calculations are based on new analytical formulation.

- transmission loss measurement method of insulation modification and data basis for all the panels of passenger compartment has been developed by PSA.

- details experimentation in wind tunnel have been conducted by SAINT GOBAIN VITRAGE and PSA to create a data basis for panel modifications.

Two new methodologies for design transparency modification were formulated by PSA. One of this methodology has been developed and tested by PSA and SAINT GOBAIN VITRAGE, and implemented in the prototype tool by HEAD ACOUSTICS.

+ A new human hearing model was developed by HEAD ACOUSTICS and applied

• Prototype development (hardware and software)
- binaural multi-input recording system (HEAD ACOUSTICS)
- binaural simulation and modification system (HEAD ACOUSTICS)

+ Test of the prototype by car manufacturers (PSA) and supplier (SAINT GOBAIN VITRAGE)

6. Conclusion

The research work has been conduced with good collaboration between partners and allows to success in the realisation of the main targets and to build and test a prototype of an industrial new tool dedicated to the subjective sound quality analysis and design modification of vehicles. This tool is based on measured binaural recordings and component's modifications using simulation techniques. Research work has been conduced to define the domain of validity and hypothesis to truncate the multi-input multi-output structural-acoustic model of vehicle. Methodologies have been tested and allow to design modification of vehicles component corresponding at the domain of validity previously defined. Sources, elastic mounts and panel surrounding the cockpit can be modified in several situations according to the correct data recording and validity domain. The component modifications can be realised using data basis of experimental or numerical physical characteristics of the modified component. A full hybrid model has been developed and can be applied to listen to the modifications of components. Model of the human ear has been developed and applied to define better index for sound quality evacuation. Future work and integration of the research work of this project will enlarge the capability of the existing prototype tool which has been tested successfully by automotive car manufacturers and suppliers.

The improvement of vibrational acoustic quality is foreseen in using the developed tool. This will lead to **a** reduction of annoyant effects not only for customers but also for inhabitants of city areas and other regions with high volume of traffic. When the modelling tool will be transferred to other fields of application, it will result additional impact effects on various environment sectors.

7. Acknowledgements

The project co-ordinator and all partners want to express on behalf of the consortium their acknowledgement to the European Commission for the decision to support the project and to provide subsidy finding in the context of the programme BRITE EURAM dedicated to Industrial and Material Technology.

We also want to acknowledge the EEC Co-ordinators which have supervised the project so kindly and efficiently at the beginning, then at the mid term and at he end. Let us name Mr ANDRIEU and Mr KRUPPA which assume respectively the co-ordination of the beginning and the end of the project.

The research work realised in the context of the BRITE Program has been judged by the partners of good quality and the co-operation very efficient.

This project was the starting point of an intense collaboration between the three partners and help them to increase their expertise and the application to the research for development of their own activities.