SYNTHESIS REPORT

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EXASYSDE SYNTHESIS REPORT

ABSTRACT

The principal aim achieved from the EXASYSDE project was the development of an integrated design procedure for the vehicle exhaust system, according to the following industrial targets:

- a durability of the exhaust system downstream of the catalyst equal to 80.000 km or 4 years, with design procedure optimisation and the use of new materials having a cost as low as possible;
- 30% lower emissions in term of unburned hydrocarbons and nitrogen oxides;
- 3-way catalyst having a conversion efficiency drop not higher than 15% at the end of the useful car life;
- an exhaust noise reduction share proportional to the overall vehicle noise reduction from 77 dB(A) to 71 dB(A);
- 3 % increase of fuel economy at still acceptable vehicle performance.

The secondary objective of the project concerned the reduction of the exhaust system design costs and time to market , with the use of the newly developed methodologies, by 20% and 30 % respectively.

Among the tools and procedures developed during the project, those concerning the prediction of tailpipe noise and exhaust emissions gave a substantial contribution to the achievements of the objectives. It has been proved that these tools - simulation codes, computational procedures and design guidelines - can be used as design tools for exhaust systems.

INTRODUCTION

The work performed by the eight partners during the EXASYSDE project concerned four main areas: fluid dynamics, acoustics, catalytic converter operation, materials. Two exhaust systems have been built and successfully tested, thus validating the procedure and the design tools.

Apart of the exhausts system prototypes, the achievements of the EXASYSDE project are summarised in the following list, where the first five items represent the core of the design methodology.

1. Procedure and tools for 3-D computational prediction of gas flow in” exhaust manifold and catalytic converter, under steady and pulsating flow conditions.
2. Different computer codes for the simulation of the acoustical behaviour of silencers and the prediction of tailpipe noise simulation, also including flow-noise, engine performances, active noise cancellation and the extension to the intake system.
3. Design guidelines for the optimisation of flow-noise, shell-noise, catalytic flow distribution, silencing system layout, materials choice.
4. CAE methodology for exhaust after-treatment optimisation, including 3-way catalytic converter transient operation, converter ageing assessment, catalyst formulations database.

5. Methodology for FEM modelling of exhaust systems and predicting surface sound radiation , with extensions to the sound field in the car underfloor and noise transfer into passenger compartment.
6. Experimental procedures for Laboratory, test rigor real operation measurements of flow distribution in the catalyst, flow-noise, shell-noise; COOI and hot corrosion resistance.
7. Procedure for the objectivation of subjective noise.
8. New ageing cycles for catalytic converters.
9.Extended possibilities for the material choice;
10. Improved catalyst formulation, considering aged converter efficiency and noble metal cost.
11. Guidelines for optimised welding of aluminised steels, with respect to corrosion and fatigue resistance.

The achievement of the primary objective, the development of integrated design methodologies, has been pursued with the investigation of several aspects which contribute to the global performances of the exhaust system: existing tools have been improved and new ones have been developed. The first four tasks of the EXASYSDE project were devoted to this work, that concerned fluid-dynamics, acoustics, catalytic converter operation, materials and durability aspects. The output of tasks 1 to 4 consists of a number of simulation codes, predicting tools, design guidelines and procedures: this material has been organised in task 5, where a design procedure has been established.

The reduction of system design costs and time to market has been achieved with the use of the above mentioned design procedure, which makes an extensive use of rapid prediction tools, in particular for exhaust emissions and tailpipe noise assessment. The required number of prototypes and measurements can be therefore mainly focused on those items where computational predictions are not yet competitive. As a consequence, costs and time required by the design phase are substantially reduced,

TECHNICAL DESCRIPTION AND RESULTS

The whole project was divided into 6 tasks:
1. 3-D modelling of hot gas flow in the exhaust system;
2. Acoustics;
3. Exhaust emission control;
4. Durability and service life;
5. Definition of the exhaust system integrated design procedure;
6. Optimised prototypes of a car exhaust system.

A technical description of the work carried out and of the results obtained in the six subprojects follows.

Task 1: 3-D modelling of hot gas flow in the exhaust system

Subtask 1.1- Steady, incompressible, isothermal flow in the exhaust catalyst.

The work performed in this subtask allowed to demonstrate the accuracy of 3-D modelling for predicting the flow distribution inside the catalytic converter in the simplest case of incompressible, non-reacting, turbulent three-dimensional flow with steady-state behaviour and no heat exchanges within the fluid nor with the ambient. The calculation were carried out with reference to the FIAT Tipo 2000 16v catalytic converter, and the results were compared with experimental data available at CRF. The intrinsic difficulty of reproducing exactly, with a computational grid, the honeycomb structure of the monoliths, due to the fineness of their geometrical scale, was bypassed by means of the introduction of a porous medium model, which allows the computations to be performed with an optimised number of cells and therefore a reduced computing time. The code STAR- CD, produced by Computational Dynamics Ltd, was used.

The numerical results are in excellent agreement with the available experimental data (velocity distribution in cross sections of the catalytic converter and pressure drop across the monoliths). Also flow separation and the formation of recirculation zones inside the diffuser (fig. 1), due to the large increase of cross-sectional area in a short length, compare very well with flow visualizations performed with the RIM (Refractive Index Matching) laser Doppler velocimetry in subtask 3.1

Subtask 1.2- Steady, compressible, reacting flow in the catalyst.

The analysis carried out during the former subtask was expanded to include additional equations for heat transfer, mass transfer of chemical species and a state equation linking the density ρ to the pressure p and the temperature T. Deliverable results are distribution of velocities u, v, w, pressure p, turbulent kinetic energy k and its dissipation rate ε, temperature T (fig. 2), density ρ and chemical species mass fractions m_x .

However some additional difficulties were encountered:

a) the porous medium simulating the monoliths is considered a fluid, therefore it is assumed that the chemical species are immediately available for conversion within the monoliths;

b) the maximum allowed number of chemical species is three: so, if HC, CO and NO_x were” selected, H_2 and O_2 could not be taken into account.

After some start-up numerical problem,’ due to the discontinuous transition from a non reactive domain, outside the monolith, to a reactive one, inside the monolith, the obtained simulation yielded 3-D numerical results in fair agreement with theory and with experimental observations.

Subtask 1.3 – Unsteady, compressible, reacting flow analysis.

The first phase of this subtask was devoted to the building of a three-dimensional mesh of the whole exhaust system. Steady state calculations yielded an unchanging, space-distributed flow pattern under a given set of boundary conditions. The unsteady calculation started, instead, from a well-defined set of initial conditions and proceed to a new state in a series of discrete time steps. Thus, the equation stemming from the conservation principles, implemented in the first two subtasks were complemented with a term taking into account the time dependence $\partial / \partial t$. Time dependent boundary conditions were imposed at the inlet (the four branches of the manifold) and outlet. As an output of the computations the time and space varying fields $f(x,y,z,t)$ have been yielded.

During the second period of the work, CRF performed the numerical simulation of a 3D periodic time-varying flow within an exhaust manifold and the exhaust tubing down to to the catalytic converter. It was deemed that, in order to provide the partners with a methodology usable with present-day computer resources, a simulation excluding the catalytic converter, but including all the interesting features upstream of it, could give an insight in the 3D flow within the exhaust system. The calculations required no more than 3 CPU days, thus a methodology for 3D fluid analysis of the exhaust system has been provided.

Task 2: acoustic.

Subtask 2.1 – Flow noise.

Tailpipe noise is dominated by the engine combustion noise, "breathing noise", at low engine speeds and by aerodynamic noise, "flow noise", at higher engine speeds. The aim of this subtask is to arrive at deign rules for flow noise minimisation and at a semiempirical method for flow noise prediction. the work has been split in three phases:

- understanding of physical phenomena
- simulation of flow noise on a "test rig
- development of a semiempirical model and its integration into a 1-D linear acoustic simulation code.

After the a survey on the existing flow noise approach, a test rig for flow noise measurements was set up, and experiments were performed on the test rig, engine dynamometer, chassis dynamometer and anechoic chamber. During this set of experimental tests it was found out that flow noise of bent tailpipes and flow noise of silencer internal are specifically different. Therefore additional studies on the flow noise from tailpipes led to the development of an empirical formula for the flow noise level of bent tailpipes.

Concerning the muffler internals flow noise, a new description based on Morphey's approach for infinite tubes has been developed, allowing excitation of resonances in exhaust system to be described. To validate the new approach an experimental silencer for measuring flow and acoustic parameters at the flow rig was designed in such a way that the dominating flow noise is caused by a defined excitation mechanism. To validate the new approach, measurements on the experimental silencer for several flow conditions have been performed. This led to the formulation of a semiempirical model for flow noise, successively implemented on a computer code, which works up to 2500 Hz and is based on the Nelson and Morphey's approach.

Subtask 2.2- Objectivation of subjective noise.

At the start of the EXASYSDE program, the sound quality assessment was only based on perceptions of one person or a small group of persons. In this subtask Gillet focused their work on *the* objective description of five typical sounds, using sound quality parameters that were currently available in the measurement technique libraries. For each of these five nasty sounds, selected from more than twenty exhaust systems, using three different engines, two exhaust system were chosen, one as the critical system, the other as reference, Since the different kinds of sound can be clearly described in terms of traditional signal processing technique and psychoacoustical parameters, the gap between a critical exhaust system and the reference one can be established through objective measuring techniques that require a preliminary signal processing (fig. 3).

In order to produce an objective measurement method able to describe the subjectively perceived noise, it is necessary to investigate how each of the five noises’ could be technically measured for other vehicles with different engines and exhaust lines in the same way.

Subtask 2.3- Acoustic theory and 1-D modelling.

This subtask aimed to the development of a computer code for predicting level and spectral characteristics of the noise generated by flow pulsations at the tailpipe, the so-called “breathing noise”. The work carried out followed two directions, that joined at the end of the activity, namely: non linear time domain fluid-dynamic modelling, performed by CRF, and linear acoustic modelling, performed by ISVR, that were merged together by ISVR in a hybrid time and frequency domain method for tailpipe noise prediction.

CRF contribution.

The fluid dynamic code (MARK14), previously developed at CRF, was implemented with the addition of two modules: a thermal module for calculating the temperature distribution along the exhaust line, considering heat transfer by conduction through the pip wall, convection and radiation; an acoustic module for spectral analysis of pressure time histories in selected locations of intake and exhaust lines, calculation of radiated noise and engine order tracking. In this way an integrated methodology, based on the” new code (MARKPLUS), was developed, able to simultaneously take into account engine performances and noise attenuation.

A FIAT Tipo 2000 16v engine with complete intake and exhaust system was modelled with the MARKPLUS code, and, at the same time, a FIAT Tipo car was extensively instrumented with pressure transducers and thermocouples along the exhaust line, from manifold down to the tailpipe. Experimental results, obtained in several operating condition on a chassis dynamometer in a semi-anechoic chamber, were compared with numerical prediction in terms of mass flow rate, backpressure, pressure fluctuation and radiated noise: the agreement was quite good.

ISVR contribution.

The modelling work in the frequency domain begun with the simulation of chambers with flow across a perforated pipe; the acoustic behaviour of such a silencer was assessed and the dependence of the acoustical impedance on flow velocity was determined. To support the modelling activity, a test rig for acoustical measurements on silencer components and exhaust systems was built. The examined silencer is supplied with air from a silenced fan, and white noise is generated from a high impedance source.

The prediction model of the acoustic characteristics of complex silencers has been successfully validated for cross flow, reverse flow and reverse cross flow silencers. In addition, the acoustic influence of packing materials in exhaust silencers was investigated and empirical expressions for fibre glass and basal wool were found.

Hybrid method.

A simulation technique, the “hybrid method”, for tailpipe radiated noise predictions has been carried out by ISVR: basically it combines a frequency domain model of the acoustic characteristics of the exhaust system with the time domain simulation of the engine thermodynamic cycle. In order to validate the domain matching it has been necessary for ISVR to develop its own time domain code.

The hybrid method was validated in two test cases: a 1.6 liter 16v engine, for a new European sports car and the FIAT Tipo 2000 16v. It gives very encouraging predictions of narrow band spectra for both intake and exhaust radiated noise up to 500 Hz.

Subtask 2.4- Surface sound radiation from exhaust systems.

The aim of this subtask was to acquire a better understanding of the influence of the main design and production factors on the surface radiated noise by means of an exhaustive experimental study. Moreover, to predict the surface sound radiation, was developed and validated a method based on finite element simulation. The experimental activity was mainly performed by Gillet, while ISVR focused their work on FEM simulation.

Here follows a list of the principal activities carried out during the subtask:

A) *Design parameters of silencers and their influence on shell noise.*

The shell noise radiated from silencers has been examined both in cold and hot conditions, using different measurements methods. In particular microphone, laser vibrometer and inertance measurements (fig. 4) were performed evaluating the impact transfer function a/F. The behaviour of silencers at high temperatures, due to expansion differences between imer and outer parts, has become stiffer and thus quieter; natural frequencies also change.

A comparison among different specimens of a standard production silencer showed discrepancies up to 20 dB: the critical factor is the connection between shell and buffles (welding together shell and buffles gives the best result in term of shell noise, but could cause corrosion problems). A statistical experimental plan was used to determine the influence on shell noise from the following parameters: shell thickness, number of shells, connection between baffle and shell, number and position of the baffles. The obtained design guidelines serve as help in optimizing the silencer construction in early stages of development, when the price is an important figure.

B) *Shell noise measuring procedure.*

To define a shell noise standard measurement procedure we have to face with two main problems: the influence on the sound radiation from the car floor and the road, and the. influence from other noise sources. If the measurements are performed in the near acoustic field, the velocity of the shell can be measured without any influence from other noise sources and also independently of the floor and road radiation. Of course the acoustic field should not be reactive (an anechoic or semi-anechoic chamber is required). On the other hand, the measurements in the near acoustic field do not allow to take into account the radiation coefficients. However, the measured value is proportional to the radiated noise, and when this value is minimised or reduced, the shell noise will also be reduced by the same amount.

C) *Modal analysis on a FIAT Tipo 2000 16v exhaust system.*

This activity begun with a structural variation test: the transfer functions of two production exhaust systems were compared to check if any important differences in natural frequencies and damping occur. The observed differences were limited within the 10%. The same test proved that the structure is linear up to 1500 Hz: above this frequency, a shaker must be used for the excitation to obtain a good coherence.

The modal analysis on the FIAT Tipo exhaust line yielded the following results: resonance frequencies with their modal damping, mode shapes, examples of different transfer functions. The middle silencer ‘was found to be the most critical with respect to shell noise (fig. 5).

D) *Pressure fluctuation inside the silencers.*

Pressure fluctuations inside the exhaust line were recorded in 50 measurement points, in order to provide ISVR with input data for forced response calculations. Another output of this activity was the comparison with acoustical calculations of sound pressure levels in the exhaust system.

E) *FE modelling of the exhaust system.*

ISVR modelled with Finite Elements method the FIAT Tipo 2000 16v exhaust system; the double skin structure of catalytic converter and silencer was initially modelled with two shells connected by small beams and the connection between shell and baffles was modelled in such a way that baffles could be easily moved. In a further phase of work, the modelling details have been slightly modified in the light of some experimental work: as result, the double skin structure was modelled as a single skin but with a modified Young modulus (this reduced the model size considerably).

F) *Validation of the analytical model and of forced response calculations.*

The FE model of the catalyst and of the front and rear silencers have all been processed and compared with the experimental results provided by Gillet. The forced response of the system has been predicted for three engines speeds, using input forces derived from pressure measurements taken by Gillett on a running engine. This model has been validated by Gillet by measuring the velocities of the shell vibration of each silencer.

As result of the ISVR activity the use of the FE method to predict the forced response of the silencer system has proved to be a very satisfactory technique.

G) *BEM and SEA calculations.*

The task of predicting sound radiation from the shell using boundary elements methods and of predicting the resulting vehicle interior noise with the Statistical energy Analysis is the main target of this work. The SEA approach is principally experimental and involves the measurements of the SEA parameters governing the flow of acoustic energy on a FIAT Tipo 2000 car. The BEM model extends the FE one to sound radiation from the vibrating shell of the silencer and essentially provides an input sound power to the SEA model.

A comparison between BEM and SEA results can be made by considering the acoustic energy level in the underfloor space predicted by the two methods.

The boundary elements and nodal results of the FE model could be easily converted to input data for the BEM code SYSNOISE. In this way the acoustical energy levels in the car underfloor were obtained and used as a comparison with underfloor conditions calculated with the SEA: a close cm-relation between the two techniques was found. This was done in order to predict the noise transfer to the car interior with the SEA method.

As an applicable predictive technique, the project has proven that it is possible to interlink the FEM, 13EM and SEA in order to compute noise transfer from the exhaust system shell to the car passenger cavity.

Subtask 2.5- Active noise cancellation.

The final goal of this subtask is the assessment of the performance of active exhaust noise control and its physical requirements as a function of its technological characteristic. To meet the target, reference is made to a front wheel drive Lancia Dedra car powered by a four cylinder, two liters, engine with catalytic converter. The silencing system of this experimental car consists of an intermediate muffler, downstream of the catalytic converter, and a rear muffler. For the purpose of this study the rear muffler was replaced by an active muffler unit, which basically consists of a sound sensor element, an electronic control unit and an antinoise generator. The electronic controller receives a synchronisation signal from a shaft encoder installed on the engine and the noise signal from a sound sensor located near the exhaust tailpipe; then a control unit sends the antinoise signal to the loudspeaker via a suitable amplifier. The engine cycle harmonics contain most of the energy of the exhaust noise, so the feedback algorithm focused its attention to the sichronised signal from the encoder to decide the frequencies spectra of the antinoise signal. At the basis of the present study there are comparison tests between two algorithms: FFT (Fast Fourier Transform) and MDFT (Moving Discrete Fourier Transform). The latter revealed to be more satisfactory in terms of fast tracking capability.

Different aspects must be taken into account when an electronic muffler is designed: the principal is the flow noise optimisation, whose responsible are the preceding passive elements and the active muffler geometry (remember that the electronic control is devoted to the breathing noise cancellation), moreover the thermal insulation of the Loudspeaker and the electrical power consumption must be supplied.

In a second phase of the work a real active muffler, in which the destructive interference between noise and antinoise takes place in a mixing chamber inside the exhaust system, was built. The experimental validation shown that the cancellation effect on the second order was quite good (fig. 6). This feature gives a poor contribution to the overall A-weighted sound pressure level during a full load acceleration (because the flow noise contribute was strong), but is appreciable during a deceleration and in different steady state conditions.

Task 3: exhaust emission control.

Subtask 3.1 - Measurements of the main constants which characterise flow and reactions in 3-way catalyst.

The activity carried out by CRF and ASAC during this subtask was devoted to provide LAT (Laboratory of Applied Thermodynamics) with experimental data concerning flow

(CRF) and chemical reaction (ASAC) in a three-way catalyst, necessary for the development of the simulation code of catalyst operation.

In particular, CRF carried out experimental investigations of flow distribution in the monoliths using two different techniques: laser Doppler velocimetry (LDV) with the refractive index matching (RIM) and hot film anemometry.

For laser Doppler velocimetry, a model of the inlet diffuser of the FIAT Tipo 2000 16v catalyst was built , in actual size and in transparent Plexiglas. The exhaust gas was simulated by a particular mixture of hydrocarbons, whose refraction index matches that of Plexiglas. The measurements were performed according to Reynolds similitude and the velocity flows in the inlet diffuser and on the inlet face of the monolith could be visualized (fig. 7).

A second technique, faster and less expensive than LDV-RIM, was developed by CRF: it is based on hot film anemometry and allows an accurate mapping of the velocity field in the monolith. Air is blown in the actual catalyst with its inlet pipe and diffuser, with mass flows according to Reynolds similitude. The flow field in the monolith is measured in a section immediately downstream of the monolith, by removing the outlet cone, The individual jets from the monolith channels do not mix together within a distance of about ten diameters downstream of the exit face. The anemometric probe moves in a plane within the non mixing distance and scans the monolith area: suitable signal processing provide the axial velocity map. It has been experimentally observed that removing the outlet cone has a negligible effect on flow distribution.

Concerning a good conversion efficiency, the main required features are good thermal stability and low light-off temperature, while noble metal kind loading and ratios as well as washcoat composition, are the factors affecting the aged converter efficiency. Both Pt/Rh and Pd/Rh formulations were selected: the first one because of its common use by European manufactures, the second for its good light-off performances and lower cost. Te-n catalysts, 2.66” diameter and 3“ long, of each selected formulation were engine aged according to ASAC’s TAL205 procedure, for 20, 40, 60, 80 and 100 hours. Pt/Rh and Pd/ Rh catalysts were simultaneously aged on the same engine..

Subtask 3.2- 1-D modelling of basic reactions occurring in a 3-way catalyst.

According to the work program, in the first six month of the EXASYSDE project, LAT developed a fully transient 1-D model of the catalyst and the related computer code. The model, initially based on computation of heat and mass transfer in a single channel using a four reaction kinetic scheme (CO, HC and H_2 oxidation, NO reduction), was successively refined with the addition of gradual improvements.

A significative development of the model was the incorporation of an initial oxygen storage submodel, that allowed a significant improvement in the prediction of the catalyst performance during highly transient driving modes. Moreover the code was tested against experimental data supplied by CRF. The following tests were performed: light-off tests, modulated air/fuel ratio tests, ECE 15 driving cycle; the light-off predictions were found to be satisfactory (fig. 8), in the modulated air/fuel test the code required further improvements. As regeards the ECE 15 driving cycle, significant discrepancies between computational and experimental results were found in the light-off behaviour.

The following issues were then investigated: model tuning procedure; accuracy attainable with the code; improvement in the code prediction capabilities; introduction of a scheme for ageing calculations; improved simulation of transient phenomena, evaluation of certain design parameters affecting overall performances of 3-way catalytic converters.

During the last few months it was observed that the computer code, using the simple reaction scheme (five reaction), showed a certain weakness in producing accurate results for instantaneous HC and NO_x emissions. Therefore it was decided that a more extended reaction scheme with improved kinetic expression should be employed. A sixth reaction, the steam reforming reaction $C_3H_6 + 3H_2O \rightarrow 3C0 + 6H_2$, which is activated only in the rich side, was introduced and added to the existing reaction scheme. This allowed to remove the above mentioned problems and gave rise to another tuning procedure for the new reaction scheme.

During the development of the three-way catalytic converter simulation code, an input and output user interface for the program was created. Now the computational optimisation of 3-WCC can be carried out by parametric examination of the important factors whhich affect catalyst behaviour. LAT, in cooperation with CRF, has formulated a preliminary version of a prediction methodology for the comparative assessment of different design approaches regarding catalyst durability.

The work performed in this subtask has provided a fundamental tool to assist exhaust after-treatment system design and optimisation, and has been furtherly developed in task n. 5.

Subtask 3.3 - Optimisation of the aged catalyst versus gas flow and conversion efficiency.

The aim of subtask 3.3 is to optimise the noble metal loading and ratios of the selected catalyst formulations, considering the effects of the catalyst volume, in order to reach the after ageing performance goals fixed by the project. The work has been carried out according to the following steps: definition of the catalyst formulations, engine ageing of the catalyst, tests of the aged catalysts. In order to better simulate the ageing of catalysts on the field after the 1999 new legislations, it has been decided, in agreement with LAT and CRF, to develop a new engine ageing cycle able to reproduce the more severe temperature and Air/Fuel conditions expected.

A two-mode cycle has been designed: the first mode at $\lambda=1$ and high inlet gas temperature (900- 950 ‘C), the second with a lean lambda peak. These two different cycles were tested using two catalyst formulations with well known performance behaviour: Pt/Rh high temperature commercial catalyst and Pal-only high temperature commercial catalyst. The results obtained showed that both formulations has deteriorated more than they normally do with other ageing cycles.

Following the defined engine ageing procedure, real scale catalysts impregnated with four different noble metal loading and ratios, for each of the two formulations defined in subtask 3.1, were performed.

The’ engine dyno testing of the aged catalyst allowed to draw’ the following conclusions: 1) results coming from the tests on the reference catalyst (always the same for each formulation) put in evidence the good repeatability of the ageing procedure;
2) the Pd/Rh formulation gave the best results also compared with the Pt/Rh formulations.

Task 4: durability and service life.

Subtask 4.1- Geometric optimisation of exhaust line.

The goal of this subtask is to identify the main stresses generated by engine vibrations and temperature and evaluating different materials in these conditions, choosing the best compromise and eventually proposing modifications of the design of the exhaust line.

In the first twelve months, the work performed moved along three directions: collection of technical information about the exhaust line (geometry, operating temperatures and vibrations), selection of the materials to be tested, evaluation of the selected materials according to representative tests.

The first part of the work was performed by CRF, SOLLAC earned out the remainder of the work. Two aluminised steel (Alusi 13HT and Extratherm A, SOLLAC trademarks) were selected for the test; suitable test procedures were defined and fatigue tests were carried out at different temperatures in bending conditions. A modal analysis was added to the fatigue tests in order to find the most stressed points and the strain levels reached in relation to vibration frequency and engine speed.

During the second year two study were performed:

- testing of different materials in laboratory experiments simulating real loading. Four point alternative bending at high temperature and tension-compression tests were performed, with different specimen geometries and positions of the welded joint (fig. 9);
- determination of the in-service loading of an exhaust line.

Two aluminised mild steel grades, aluminised low carbon steel BHT and Extratherm (SOLLAC™) were tested in fatigue at high temperatures. The influence of several parameters, which are relevant for the application in the exhaust system were determined. The endurance limit of both tested materials is high even at elevated temperature and the first comparison between materials characteristics and stress levels on an exhaust line is very positive ("safety factor"= 3).

Subtask 4.2- Cool and hot corrosion resistance.

There are two different types of corrosion along the exhaust system: the first, hot corrosion, concerns the upstream section of the line, submitted to hot oxidation by exhaust gas, the second, cool corrosion, affects the downstream section of the line, submitted to condensates.

The aim of this subtask is to determine the factors affecting the exhaust system resistance to these two kind of corrosion.

Cool corrosion.

Based on a bibliographic study, three tests were defined and evaluated with two materials commonly used *as* mufflers material: type 1 aluminised low carbon steel and type 409 stainless steel. The three test are: I) a cyclic test, II) a half immersion test, III) a boil down test. For all the tests, two synthetic condensate solutions, acid and alkaline, have been used. To compare the test results with degradation modes in service life, SOLLAC has collected failed exhaust systems from muffler repair shops: as a general rule, the same degradation modes have been found.

After having evaluated the tests, three materials were chosen for the experimental phase, according to economical criteria, temperature and corrosion resistance requirements: aluminised low carbon steel, AISI 409 stainless steel, aluminised AISI 409 stainless steel. Aluminised stainless steel specimens showed the best corrosion resistance for all the tests: no red rust is observed even after 33 days in boil down test. For the cyclic test and the boil down test in acid solution, aluminium coating of immersed parts is nearly removed.

Hot corrosion.

As regard hot corrosion, the behaviour of different materials (aluminised steel BHT and Extratherm in comparison with the reference material stainless steel AISI 409) is compared during laboratory air oxidation tests. Two kinds of tests have been selected: isothermal test, 50 hours at temperatures from 400 to 850 'C, and cyclic test, 25 minutes at temperatures from 400 to 850 °C followed by 5 minutes at ambient conditions, repeated 130 times. The tested samples are flat samples, tubes or flat samples with an uniaxial tensile deformation of 20%.

The effects of temperature are damaging of the materials and destruction of the system (previous investigations showed that the most frequent fracture points on an exhaust line are the welded zones), thermal shocks due to water pools or mechanical ventilation with extremely high temperature drops, hot oxidation due to corrosion effect of gases.

The results of the comparison were evaluated examining the evolution of grain size with temperature, the oxidation resistance of the different base metals, the behaviour of aluminised coated materials and the behaviour of the welded areas with respect to hot corrosion: Extratherrn showed in all tests the best behaviour.

Subtask 4.3- Link optimisation of the different exhaust system components.

This subtask consists of an optimisation of the links used for assembling the different parts of the exhaust system: manifold, catalyst and mufflers.

A survey was conducted, among car dealers and repairers, on linking solutions used nowadays and on failure modes in real life; at the same time, weldability studies on aluminised steel were performed. The main conclusion of the survey is that breaking or wearing of the links are never restrictive with regard to the durability of the line. When a break of a joint occurs, it is the result of a previous deterioration by corrosion of the parts, that leads to an increase of the clearance, then to harmful vibrations, impacts and stresses. So, the life of exhaust lines is limited, in a preponderant way, by the corrosion inside the muffler or in other parts.

The weldability, by an arc process, of aluminised and stainless steels has been investigated. Welding aluminised steels together, specially Extratherm, did not reveal any particular problem using a GMAW process: a set of parameters which provides satisfactory technical and economical criteria was defined for assembling exhaust lines, as well as preferred geometries for the welding zones. The same set of parameters can also be used for welding together Extratherm and AISI 409 without problems.

The welding zone is more susceptible to corrosion phenomena because of local coating damages, so an inner protection by a neutral gas like Argon seems to give very good results. However, previous studies have proved that corrosion on damaged welding sections never is a privileged location of breakings in service.

Task 5: definition of the exhaust system integrated design procedure.

The main objective of task n.5 is the integrated design procedure for exhaust systems, supported by tools such as handbook with design criteria and databases. The results of the previous tasks, in terms of experimental data, measuring procedures, design guidelines and optimisation methodologies were provided by the partners to CRF. A draft design methodology was been prepared by CRF and submitted to the partners: the concerned items are exhaust system general layout, tailpipe noise (breathing noise and flow noise), exhaust after-treatment, catalyst flow optimisation, shell noise, materials choice.

According to the partners' suggestions, the methodology considers two main steps in the design procedure, namely concept and development, and is mainly focused on the first one.

The concept phase deals with fluidoacoustical design of the exhaust line (layout definition, catalyst position and inlet shape, number, position and volume of the silencers), after-treatment system design, materials choice and simplified vibration analysis. The available tools for the concept phase are synthetic simulation codes with reduced computation time (l-D linear acoustic codes or hybrid method, catalyst simulation codes, then 1-D time domain fluidodynamic codes and, to a certain extent, simplified FE models), design guidelines and criteria for materials selection.

In the development phase, more complex tools can be used, which provide a more detailed insight into the behaviour of the different components of the exhaust line, but require longer times both for input data generation and calculations, and experimental validation: 3-D CFD, FE and BE models, BEM and SEA for shell noise and vibration, subjective noise objectivation.

However, as already mentioned, the partners' opinion is that the concept phase is of great importance for the definition of a good starting design and for the reduction of the overall development time. Therefore, part of the work was devoted to reducing the amount of time required by some of the analysis tools, with the aim to shift their use from the development to the concept phase.

As regard the databases, the collection has been limited to the database structure, since a great amount of data is concerned, and data produced within the EXASYSDE project have been stored together with previously obtained data. Then, each partner provided a description of their databases and several examples of the stored data.

Task n.6: optimised prototypes of a ear exhaust system.

Subtask 6.1- Design and construction of the two exhaust systems.

The design of the exhaust system prototypes for a FIAT Tipo 2000 16v ear was carried out according to the design procedure described above.

The main effort in the design procedure was devoted to improving the low frequency acoustical performances of the silencer system, as well as flow noise and shell noise emissions: linear acoustic codes and design guidelines were the main tools. Particular care was also devoted to the gaseous emissions and material choice, in both cases previous guidelines were used.

The “passive” prototype exhaust system, called "Passive_1" (fig. 10), consists of the catalyst and three silencers in the same position as for the standard exhaust line. With respect to this, the diameter of the connecting pipes has been reduced and the volume of the two main mufflers has been increased in order to improve the low frequency attenuation. The external shape and internal baffles have been optimised for a low shell noise design, whereas the internals have been simplified with the aim toward flow noise and backpressure reduction. In addition only silencer internals that can be modelled with the acoustic simulation codes were used. The shape of the catalyst inlet was left unchanged, since the production inlet proved to be very satisfactory in terms of flow distribution.

Also an “active” exhaust system prototype, called "Active_1", was built; it used, as rear silencer, a combined effect muffler, merging together the volume effect of the silencer and an active effect of the loudspeaker, while the first’ and second silencers were those of the "Passive_1" prototype.

The exhaust systems prototypes were designed by CRF, Gillet, GS Gilardini and ELESA and built by GS Gilardini and Gillet, with advises and supplies from the other partners.

Subtask 6.2- Car instrumentation and full scale tests of the exhaust systems.

CRF instrumented the test car with transducers, signal conditioners, acquisition systems and auxiliary devices in order to perform. the scheduled tests. Low frequency signals (temperatures, backpressures, engine and car speed) were conditioned and acquired with a PC-based system; high frequency signals were conditioned with a dedicated system and recorded with a digital (or analog) recorder.

CRF (and Gilardini) tested the prototypes with the instrumented FIAT Tipo car. The "Passive_1" exhaust line met the targets inter&s of tailpipe noise, showing an overall level lower by 5 to 12 dB(A) than the standard exhaust line, with a little backpressure increase @g. 11).

Engine-out and tailpipe emissions were measured during the ECE-EUDC and FTP75, and the results were transmitted to LAT, which will perform a simulation with the actual input data. The emission figures obtained in the European cycle with both fresh and aged catalyst comply with the EU 1996 limits, and the loss of efficiency after ageing is about 9.5% for HC and 3% for No$_x$. Thus better than the design targets. Gillet performed engine and flow bench tests concerning shell noise, tailpipe noise and flow noise: it was decided that no further optimisation of the passive prototype was necessary.

As regards the "Active_1" prototype, its tailpipe noise was unsatisfactory, due to flow noise.

Subtask 6.3 – Prototypes optimisation.

The "Active_1" prototype had flow noise problems, a limited ground clearance, and the loudspeaker was not powerful enough to reduce the second order entering the active muffler. So, it was decided by CRF and ELESA to design a second active exhaust system according to the following criteria:

- the volume of the rear silencer had to be very similar to the standard one, possibly using the same sheiks with minor modification to fit the loudspeaker;

- a substantial share of low frequencies noise reduction had to be provided by the passive part of the exhaust system, essentially the second silencer;
- flow noise had to be strongly reduced;
- the acoustical design of the rear silencer, in particular tailpipe diameter and length had to be optimised for loudspeaker effectiveness.

The design was done with CRF's INTEX code (linear acoustic code, a further evolution of SILLOS) integrated by ELESA's LFDES loudspeaker simulation software, taking into account the flow noise guidelines by Gillet. Gilardini provided for the detail design and the construction of the exhaust system.

The new prototype, called "Active_2" (fig. 12), was tested on the FIAT Tipo car: tailpipe noise and interior noise were measured with active cancellation off and on, and with different antinoise control parameters. The results were good: the overall tailpipe noise level of "Active_2" exhaust line is slightly higher than that of “Passive_l” prototype even with antinoise off. Switching on the antinoise reduces considerably the second order, but has a minor effect on the overall level (fig. 13), The cancellation effect is very good at low engine loads, for example in cruising conditions up to 120 km/h. Inside the passenger compartment there is a sensible effect at the rear seats.

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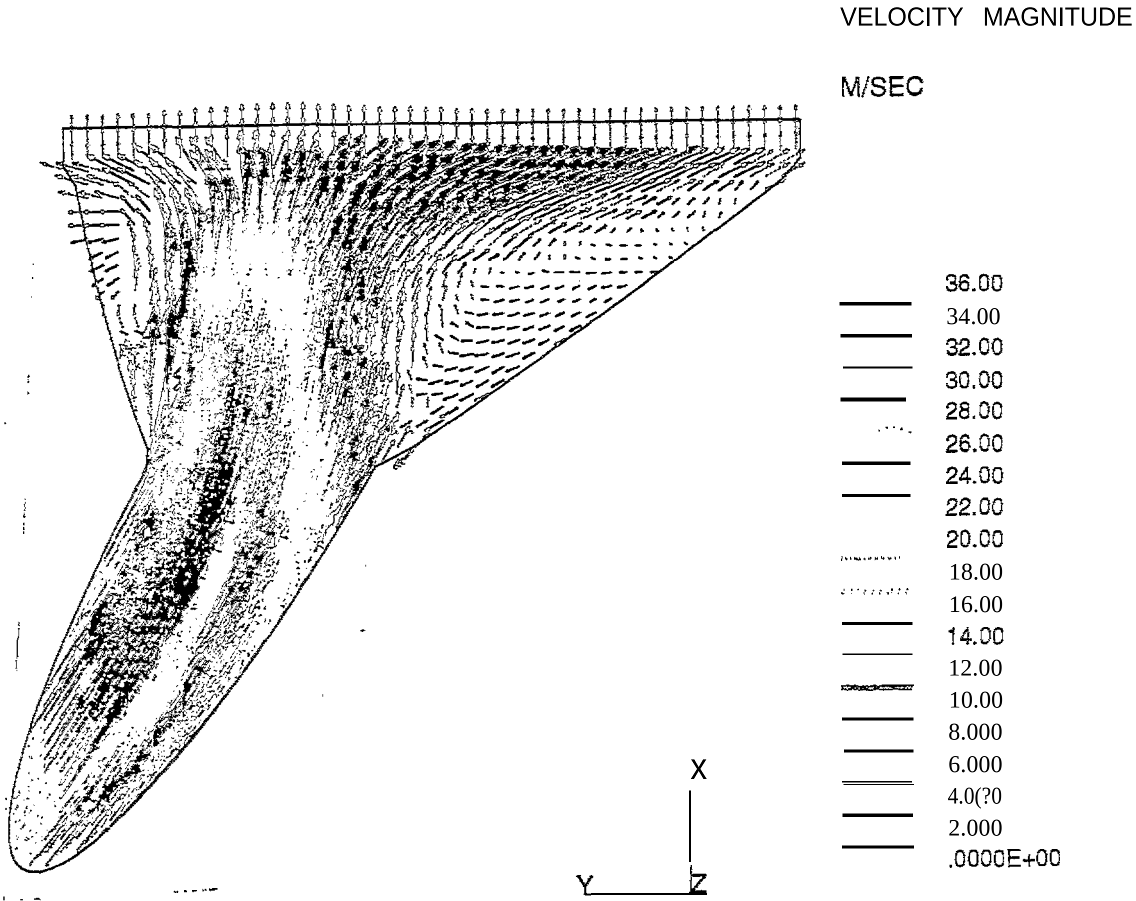


Fig. 1 Velocity distribution in the diffuser and in the first two cell layers of the first monolith, on a longitudinal section of the catalytic converter

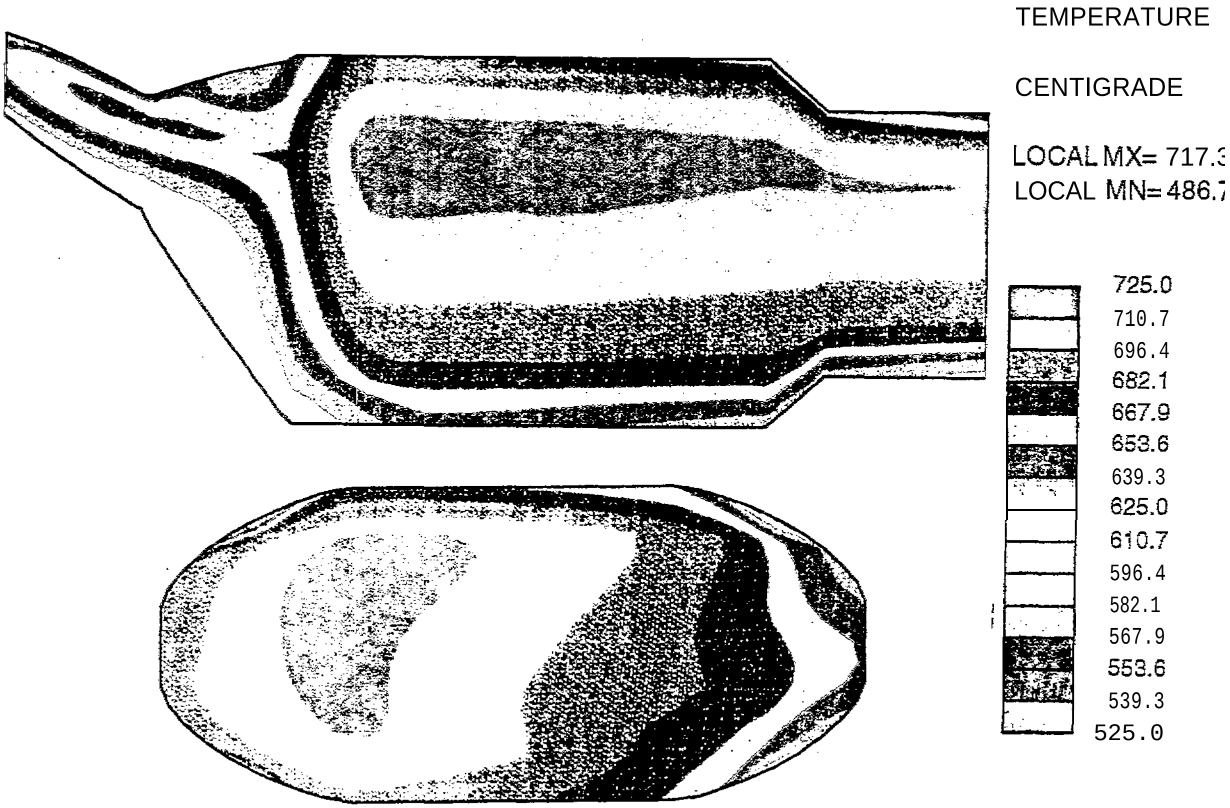


Fig. 2 Temperature distribution in a longitudinal section of the converter (above) and in a cross section 30 mm inside the first monolith (below)

"Low modulated noise" during the start of acceleration under load

lefthand side: reference system

righthand side: critical system

fluctuation strength'

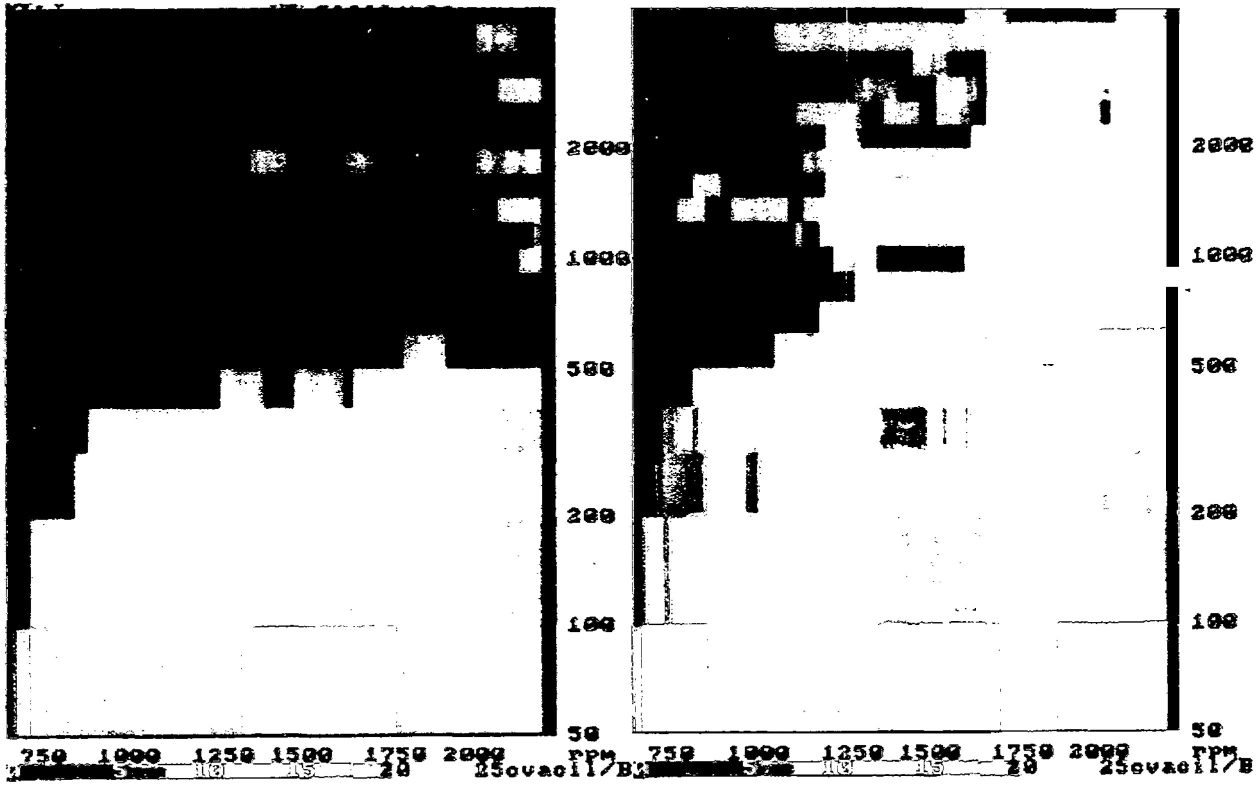


Fig. 3

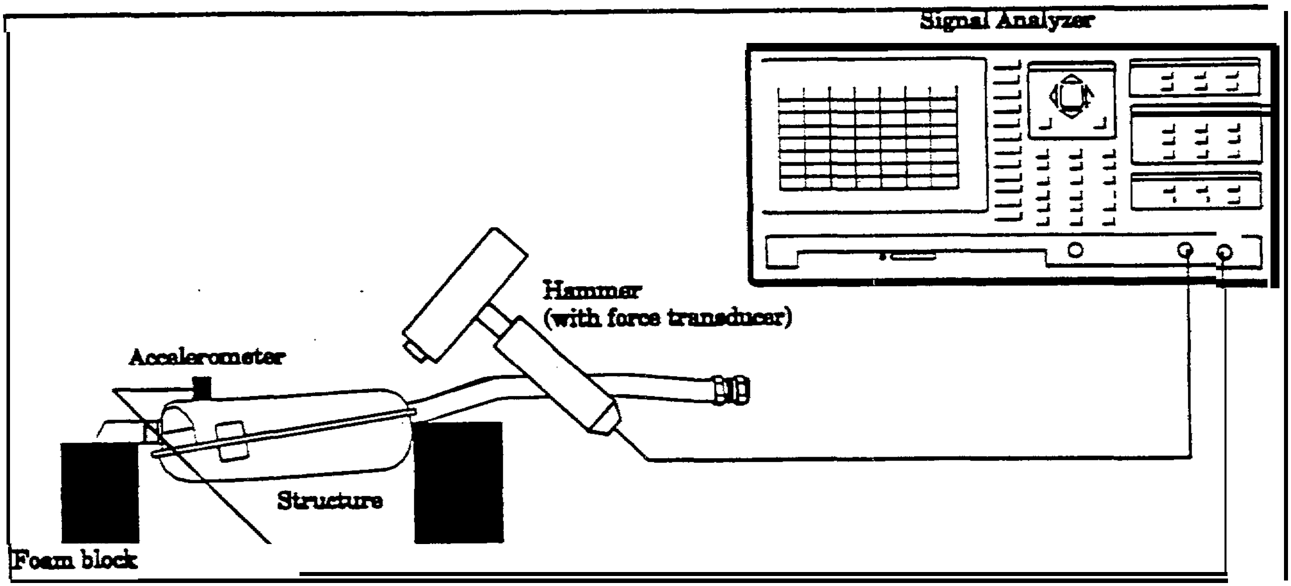


Fig 4 Set-up for inertance measurements

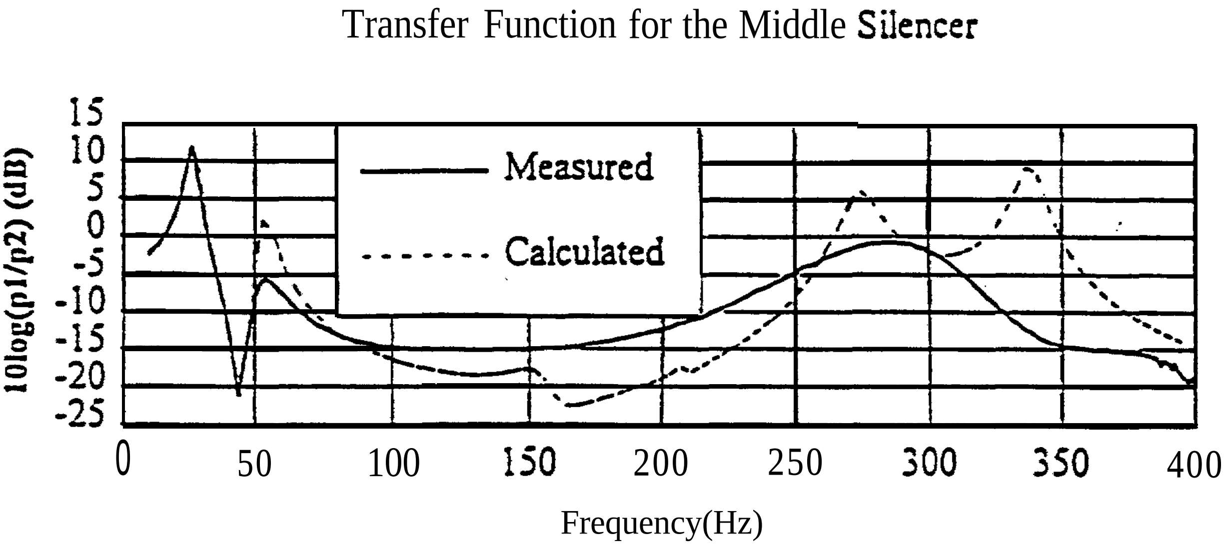
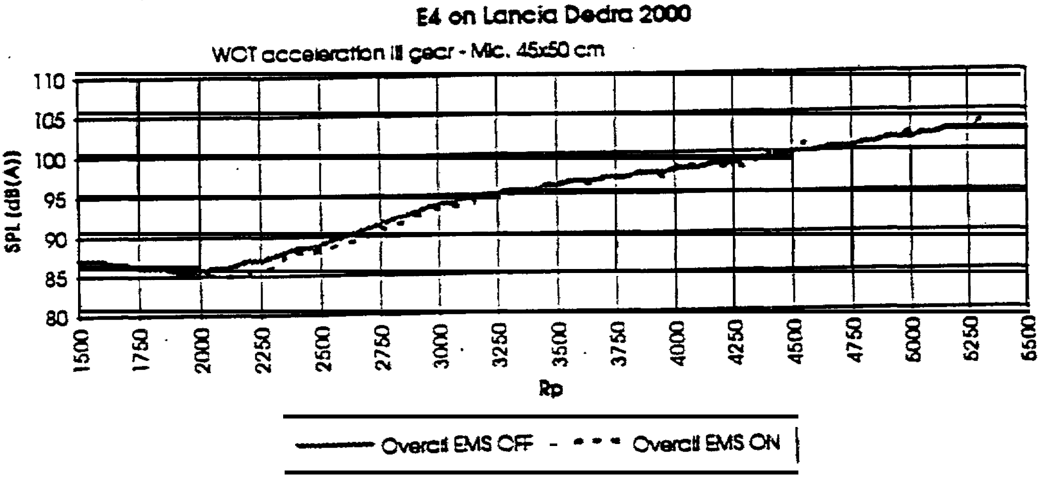


Figure 5: The measured and calculated transfer function for the middle silencer.



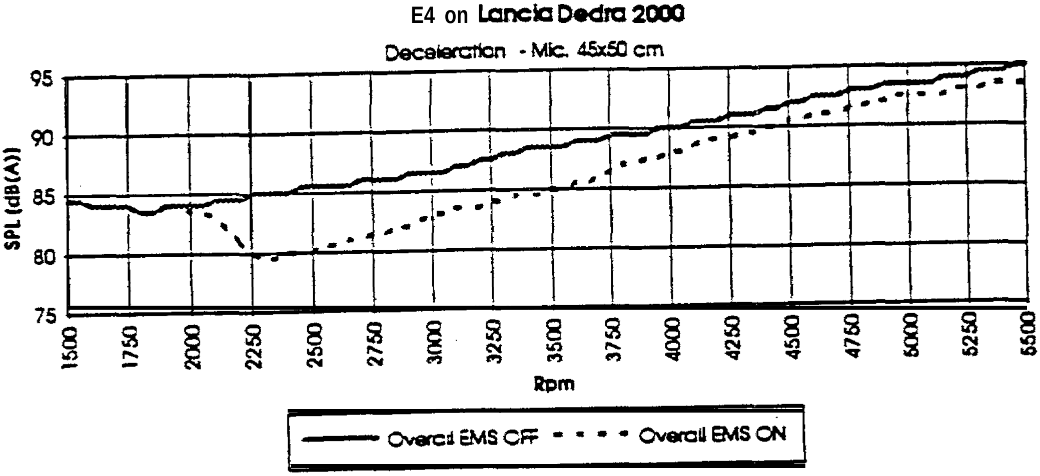
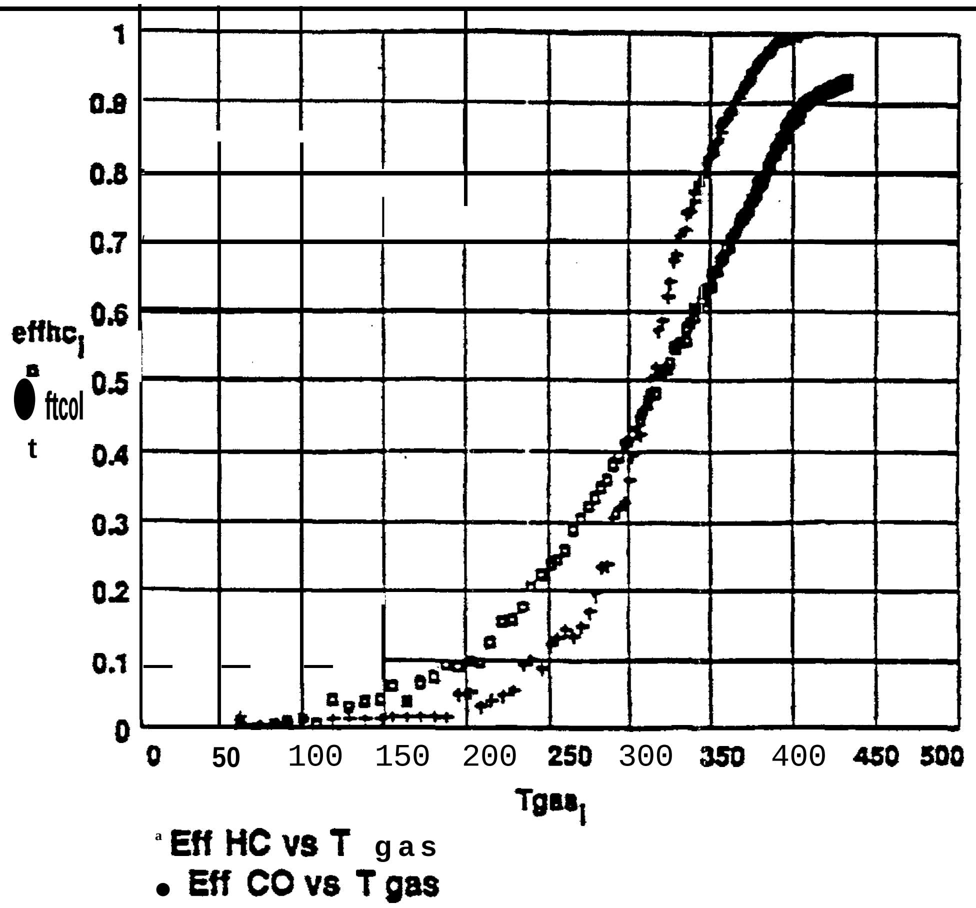
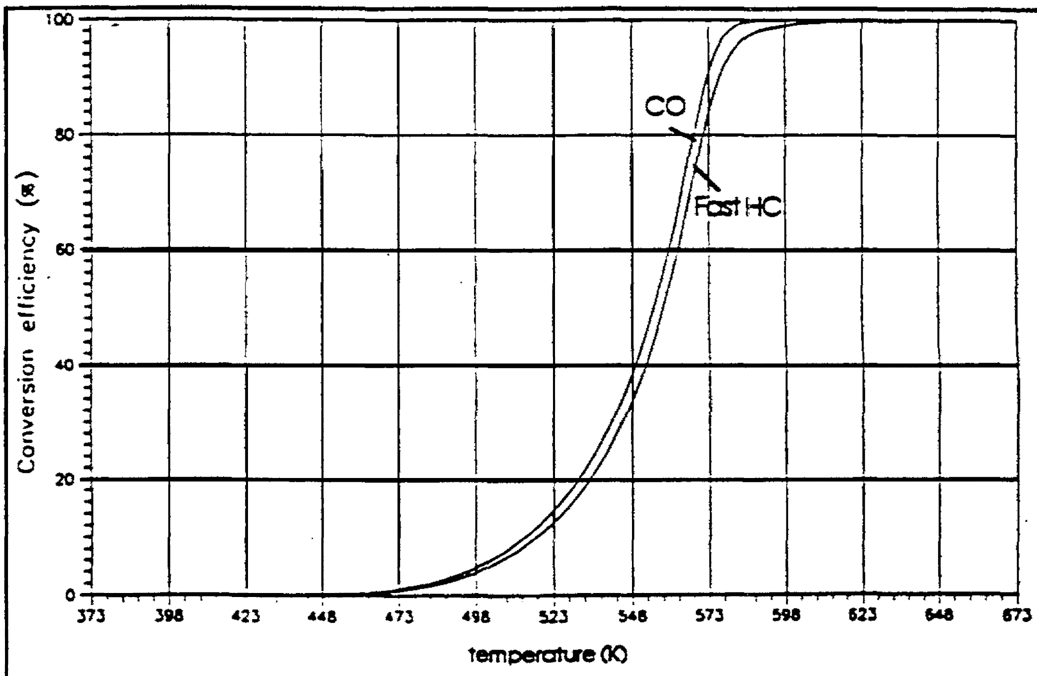


Figure 6 - II order cancelling effect on the Overall Level during a WOT acceleration and deceleration

Fig. 7



Measured light-off performance (Source: CRF)



Computed light-off performance

Fig. 8

EXEMPLES OF BENDING TESTS

EXTRATHERM

Spawn Nb	Initial stress	Stress at the stabilized cycle	Nb of cycles	Remarques
EXT3	t 36	122	443000	BREAKED
EXT8	136	124	200500	BREAKED
EXT5	131	117	544000	BREAKED
EXT9	125	109	2380000	BREAKED
EXT4	119	106	2240000	BREAKED
EXT6	114	t 00	5050000	BREAKED
EXTIO	105	104	186s000	BREAKED
EXT11	I 08	96	5560000	BREAKED
EXT12	?08	97	3960000	BREAKED
EXT13	105	93	6236000	BREAKED
EXT15	105	93	3780000	BREAKED
EXT2	102	#5	3000000	NOT BREAKED
EXT 16	97	85	9142000	BREAKED
EXT17	97	87	8750000	BREAKED
EXT18	91	75	3$650000	BREAKED
EXT1	85	85	2000000	NOT BREAKED

ALUMINIZED BHT STEEL GRADE (Weld not Worked)

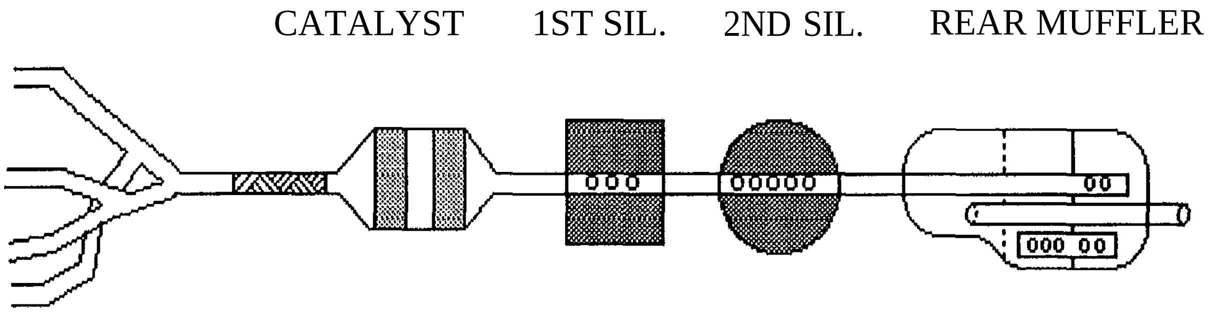
Specimen Nb	Initial stress	Stress at the stabilized cycle	Nb of cycles	Remarques
FX11	80	68	751500	BREAKED
FX12	74	?2	1202000	BREAKED
FX13	70	71	2550000	BREAKED
FX25	91	81	1 60000	BREAKED
FX10	68	80	7600000	NOT BREAKED
FX8	57	48	70500300	NOT BREAKED

ALUMINIZED BHT STEEL GRADE (Weld Worked)

Specimen Nb	Initial stress	Stress at the stabilized cycle	Nb of cycles	Remarques
FR9	74	72	92100	BREAKED
FR15	74	66	693000	BREAKED
FR11	68	63	1096000	BREAKED
FR14	68	62	2333000	BREAKED
FR16	68	59	1380000	BREAKED
FR26	68	60	2060000	BREAKED
FR32	68	60	33?5000	BREAKED
FR10	82	57	2738000	BREAKED
FR12	62	59	2240000	NOT BREAKED
FR17	62	54	2880000	BREAKED
FR18	57	4?	7530000	BREAKED
FR19	51	45	15500000	BREAKED

Sollac
LEDEPP

Fig. 10



Passive exhaust line.

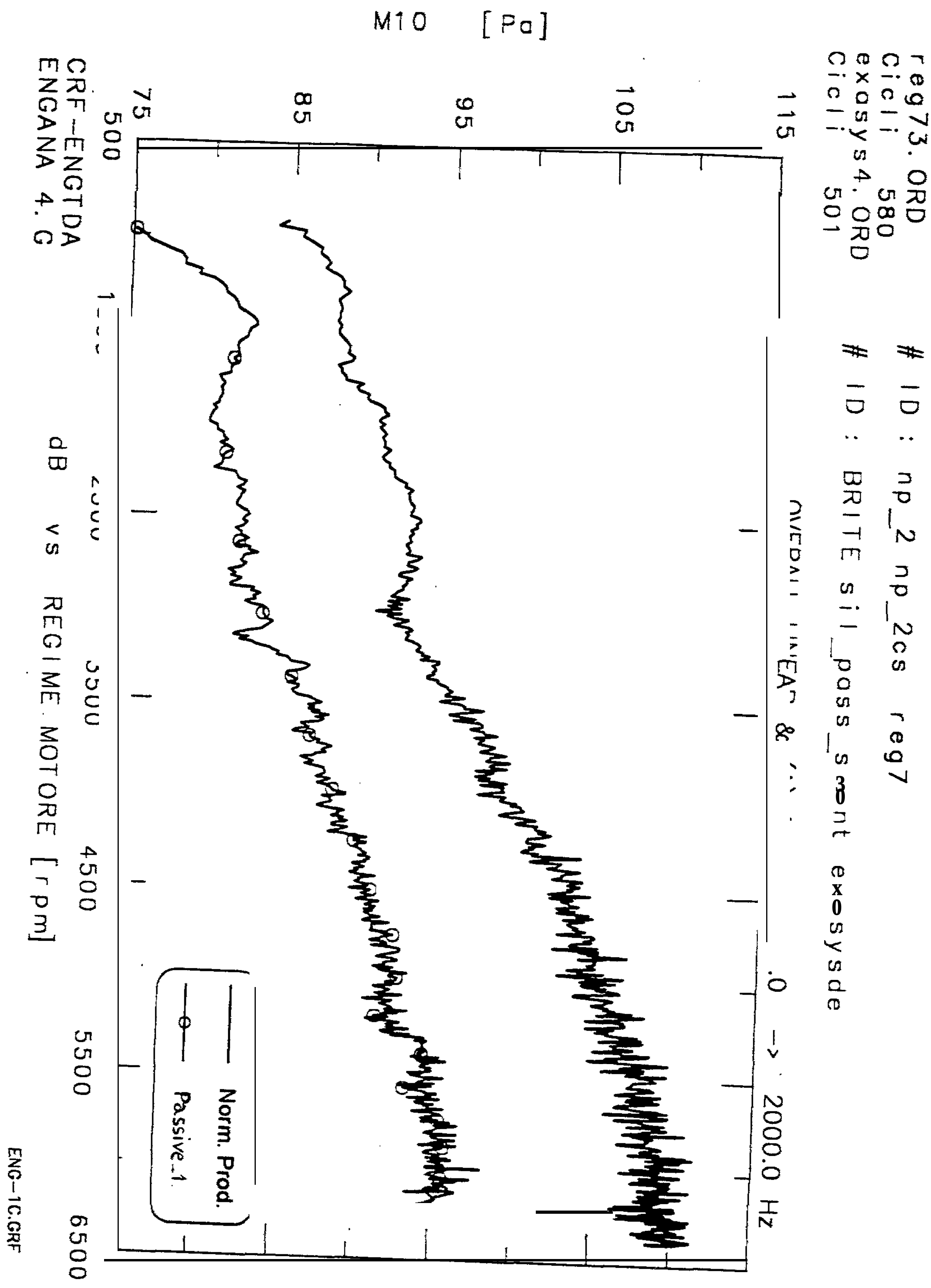
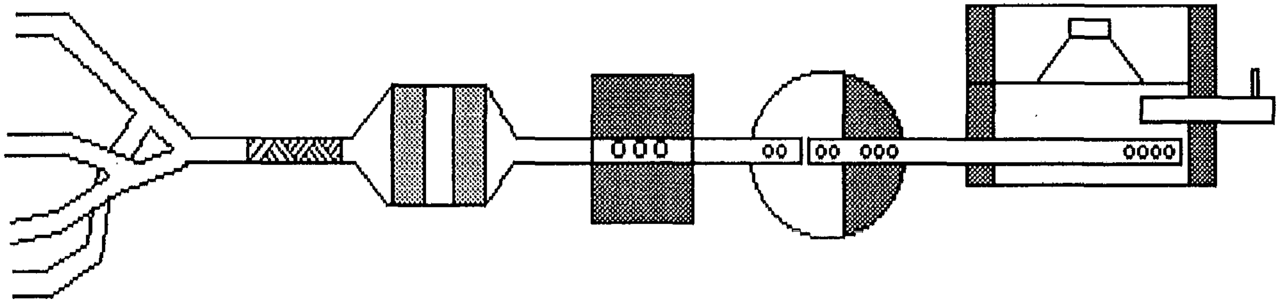

reg73.ORD
Cicli 580
exasys4.ORD
Cicli 501
ID : np_2 np_2cs reg7
ID : BRITE sil_pass_s mont exosysde
EA &
.0 -> 2000.0 Hz
M10 [Pa]
115
105
95
85
75
500
3500
4500
5500
6500
dB vs REGIME MOTORE [rpm]
CRF-ENGTDA
ENGANA 4.G
Norm. Prod.
Passive_1
ENG-1C.GRF

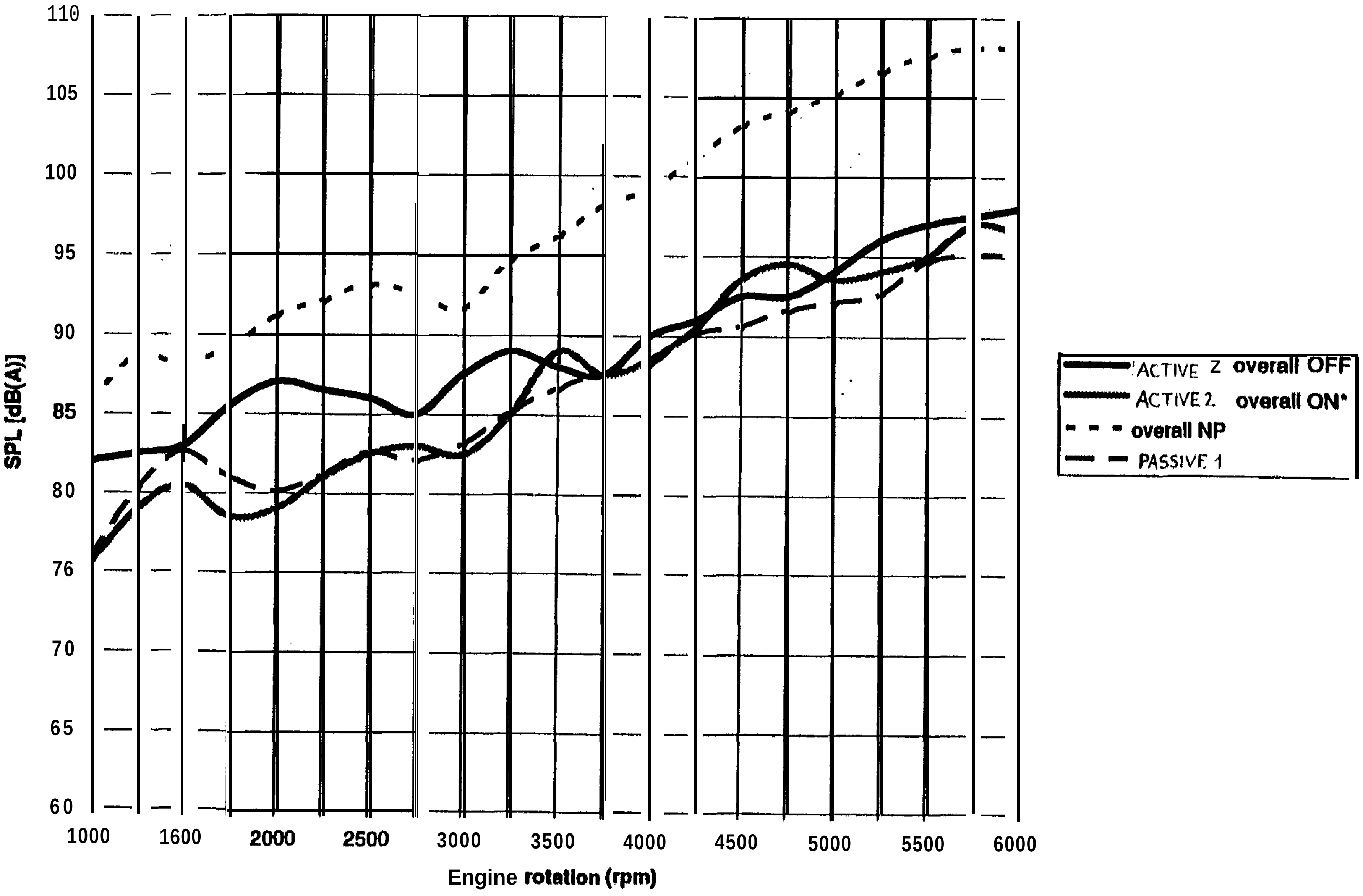
Fig. 11

Fig. 12



Combined exhaust line Active 2.

Fig.13


SPL [dB(A)]
110
105
100
95
90
85
80
76
70
65
60
1000
1600
2000
2500
3000
3500
4000
4500
5000
5500
6000
Engine rotation (rpm)
ACTIVE Z overall OFF
ACTIVE 2 overall ON*
overall NP
PASSIVE 1