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LaMoNoV: LawnMower Noise and Vibration Control – First results

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Abstract

For over 25 years lawnmowers have to comply in Europe with more and more stringent noise limits. To investigate new solutions and to provide appropriate technologies involves an increasing effort in R&D. Therefore, a group of 10 manufacturers of lawnmowers and lawnmower components established – together with three European laboratories, specialized in noise and vibration control – an ambitious industry supported research project, which started in January 2004 and ended in June 2006.

One of the main tasks of this project was to develop a computer based design tool that can be used by the manufacturers in the very early stages of the development of quieter lawnmowers. In addition to this task, which called for more knowledge of physical acoustics of components, the goal of the project was also to gain a deeper understanding of annoyance created in the neighborhood surroundings of operating lawnmowers; i.e., of the psycho-acoustic aspects.

The work has been structured in 6 work programs. Three of them are component oriented (noise + vibrations generated from blades, engines, and transmission components), one is dedicated to physics of the complete lawnmower, another one deals with subjective noise parameters, and one is focused on virtual prototyping.

The context of this project, the technical constraints and the chosen approaches have already been presented in a former paper [1]; therefore this paper is focused to the principal results obtained during the project, the industrial effects and remaining matters for future work.

INTRODUCTION

1. LEGAL AND ECONOMIC CONTEXTS

For almost 25 years regulations set up by the European Commission have defined noise limits for lawnmowers. These limits, labelled in A-weighted sound power levels, depend on the size (cutting width) of the mower. The latest European Directive 2000/14/EC, in force since 3/1/2002, has defined 4 ranges of cutting width (instead of 3 categories before) and the indicated limits are considered to be guaranteed values. That means to the measured value a so called K-factor must be added this includes uncertainties due to variations in measurements and due to the scatter in the production. Since the numerical values of the limits have been left unchanged, keeping to this procedure implies in fact a noise reduction of 1 to 3 dB(A). For most of the manufacturers significant efforts are necessary to comply with Stage I of the Directive. At Stage II (starting from 3/1/2006) a further reduction of 2 dB(A) is already planned for mowers with a cutting width in the range of 50 – 70 cm and may be extended to all sizes. In a technical evaluation [2], funded by the European Commission in order to prepare a decision on this matter, the second author has recommended to delay Stage II by 4 years, considering the foreseeable difficulties. The decision is still pending.

The European lawnmower market covered by these regulations represents approximately 4.5 million units sold per year of which UK, Germany and France absorb 2/3 of the volume. Although a trend to bigger ride-on tractors can be observed, still today 90% of the sold lawnmowers are walk behind models with cutting widths up to 50 cm, 1/3 of which are powered by Internal Combustion (IC) engines and 2/3 by electric motors.

2. ORIGIN AND SCOPE

With the introduction of Directive 2000/14/EC the European Garden Machinery Federation (EGMF), which currently comprises 14 European manufacturers and 4 National Associations, has made an effort to launch in the framework of 6th PCRD a collective research project on “Lawnmower Noise and Vibration Control (LaMoNoV).” When this attempt failed in 2003, the manufacturers decided that the 6 months of work which had gone into the preparation would be used to create an industry funded research project. During the initial stage of the project the consortium decided to concentrate on IC engine driven products with rotary blades. This decision was made with the knowledge that these types of mowers (a) were used most widely and (b) they pose the greatest difficulty for further possible noise limit reductions. The latter is caused by the physical constraints of the rotating blade and its aerodynamic interference with the deck in the most important relation to the quality of cut and the performance demanded by the users of these products.

The actual project covers mainly two R&D issues:

- design tools and techniques aimed to enable low noise design of lawnmowers using user friendly software and product-specific measurement techniques,
- create psycho-acoustic or sound quality evaluation of lawnmower acoustic annoyance level and comparison with standardized evaluation of sound annoyance using dB(A) level.

The first R&D issue deals with the development of a new noise design tool, inspired by the fact that the lawnmower noise is governed by the operation of some key components (engine, blades, power transmission parts, etc.) integrated within an otherwise passive frame. Under the action of these components the assembled machine often amplifies noise. In the LaMoNoV project an evolution strategy for noise reduction has been used. It builds on an existing generation of products with the aim of improving their noise performance. Some generic acoustic properties of the products belonging to the same class (e.g. small home lawnmowers) have been established from dedicated measurements followed by specific data processing. Once identified these generic properties and experimentally obtained noise data from real machines has been combined within a novel computation tool, the Product Noise Synthesizer (PRONS) software. Variation in parameters (e.g. characteristic mobility, modal density, and damping) as well as variation in strength of different noise inputs from the component(s) has ultimately revealed the right measures for achieving possible noise reduction. This should help the designer to synthesize a past design in a noise oriented manner, hence the name Noise Synthesis Technology (NST).

The second R&D issue concerns the annoyance of sound radiated by different types of lawnmowers. The acoustic annoyance is generally measured using dB(A) sound levels where A stands for the standardized “A - filter”. The limits of the dB(A) methodology are now obvious. These limitations can be overcome by using a newly emerging approach in noise annoyance assessment – Sound Quality Analysis. The Sound Quality Analysis combined with the Jury Evaluation of sound recordings gives a radically new insight into the degree of annoyance of different sound characteristics. In the framework of the LaMoNoV project this approach has been used in order to establish and propose new annoyance metrics. The new metrics have been compared with corresponding dB(A) levels, and, if appropriate, proposed to the scientific and industrial community as a new lawnmower annoyance descriptor.

3. CONSORTIUM STRUCTURE

The consortium is comprised of 12 manufacturers of lawnmowers and lawnmower components who finance the total cost of 1.5 Million Euros:

Austria:	VIKING
Belgium:	Toro
France:	Gaby, Granja, Honda, and Outils Wolf
Germany:	ALKO, John Deere, MTD, and Wiedenmann
Switzerland:	Briggs & Stratton

United Kingdom: Electrolux Outdoor Products

The technical and scientific work is carried out by several R&D sub-contractors under supervision of the Centre Technique des Industries Mécaniques (Cetim). Cetim is assigned to manage the running of the technological, scientific and logistic common project activities and is the sole interface to the LaMoNoV Consortium structured in the form of EEIG (European Economic Industry Group). Cetim has collaborated since 1972 with a large variety of industries and can be considered in the field of acoustics and vibrations as unique in Europe for its variety of competencies, technical knowledge, testing facilities, and awareness of industrial problems. Sectors covered include home appliances, HVAC units, refrigerating machines, garden machines, earth moving machines, machine tools, pumps, compressors, etc. As a project leader Cetim has extensive experience in the management of large Europe-wide research projects. Cetim's missions of technology developments and transfer organization make them well suited to undertake both the overall project co-ordination and execution of a majority of research and development tasks within the project.

Main subcontractors are:
The Acoustic Research Centre, University of Salford. (ARCUS)
ARCUS is a laboratory which well known in the field of vibro-acoustic source characterization and virtual prototyping, and is ideally qualified to lead the source-ranking and characterization related tasks. A. Moorhouse [3],[4] has been active in these areas for over 15 years and has made key original contributions, most notably as part of the recently completed EU funded project NABUCCO (GRD1-1999-17085). His leading position has recently been recognized by the EPSRC (Research funding council of the UK) that awarded a £200k grant to further develop Virtual Prototype techniques. This project has run concurrently with LaMoNoV, and provided important input to LaMoNoV. The Centre has a 30-year history of research projects in acoustics, and an extensive range of acoustic measuring equipment and international standard test facilities including an ISO standard listening room for psycho-acoustic testing and a recently commissioned calibration laboratory. A number of the testing activities are UKAS accredited.

HEAD acoustics GmbH (HEAD) – has about 100 employees' world wide, predominantly engineers, with its own research group. Main R&D activities refer to components and systems for aurally-equivalent recording, analysis and reproduction of acoustical data. The engagement in Sound Quality and Sound Engineering activities has been a core business since the foundation and was the origin for inventing the Artificial Head technology. In this area HEAD acts as market leader. HEAD has developed PRONS software which has been used in the virtual prototyping of lawnmowers. The main tasks of HEAD consisted in sound recording, sound quality analysis and setting up the vibro-acoustic database of lawnmower components and models to be used by PRONS software.

4. TECHNICAL PROGRAM

The project structure - see figure 1 - is derived from the adopted R&D strategy. The work plan of LaMoNoV comprises six complementary technical work packages (WP-s):

WP1 – Physics of lawnmower noise:
WP2 – Subjective noise parameters
WP3 – Blade generated noise and vibration
WP4 – Engine generated noise and vibration
WP5 – Noise and vibration of transmission components
WP6 – Acoustic virtual prototyping

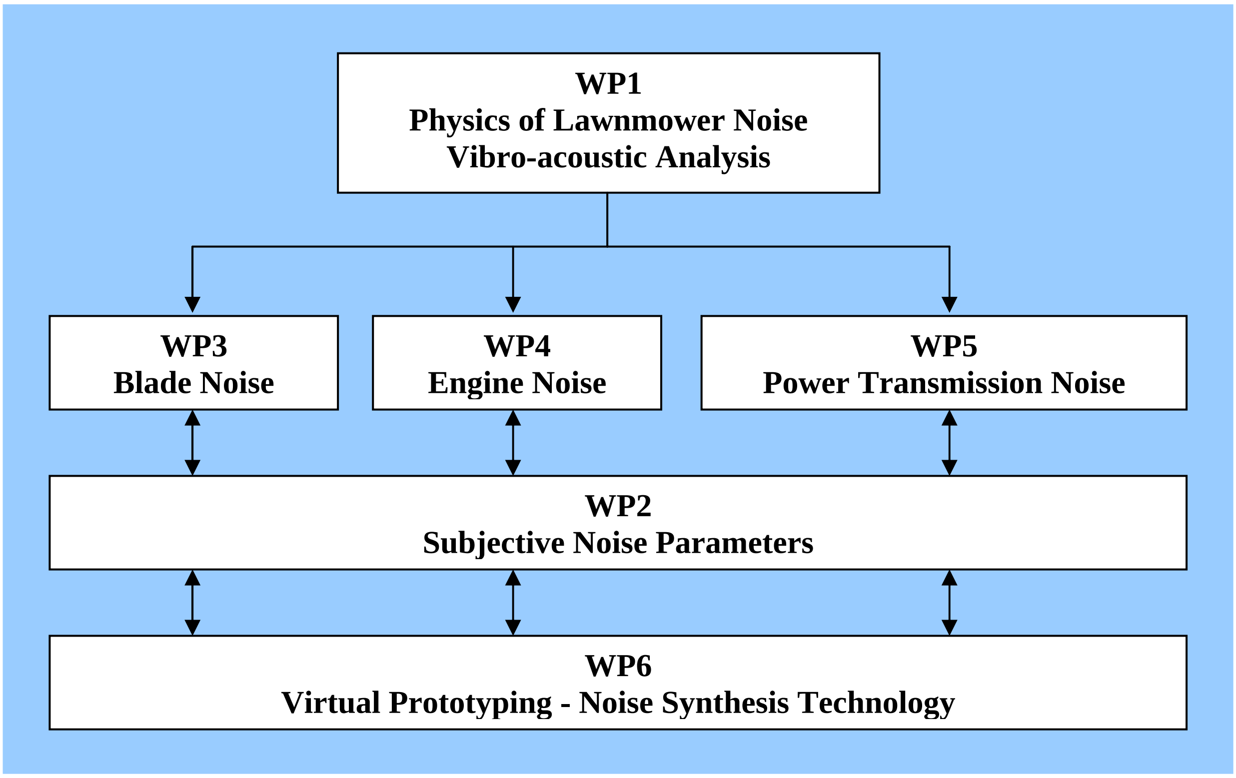

Figure 1: *Project structure*

- **WP1** aims to create know-how on lawnmower noise generation and to establish vibro-acoustic models of lawnmowers chosen for the analysis. In addition the accuracy of measurement and ranking techniques has been evaluated. This needs systematic noise and vibration measurements, source ranking, transmission path analysis as well as statistical investigations into dispersion of production variances.

  Preliminary results: 5 specimens of all 28 rotary mowers (total 140 products) have undergone detailed sound power measurements. The overall measurement results showed that all products are close to the limits as specified by the regulations. After that from all 28 rotary mower types rank order noise sources, acoustical schemes, and characterise acoustical properties of sub-assemblies were established. The acoustical properties were entered into PRONS for noise synthesis. Noise of major lawnmower sources has several tonal components and one broad band component. Tonal components are being generated by the engine and blade rotation speed. Blade mounted on shaft either directly or via non-slipping clutch gives blade and engine rotation at the same speed causing that the blade and engine noise is correlated. Another important result from these measurements showed that the blade and the interference of the aerodynamic properties with the deck are the most dominant noise factor. More information can be found in WP3.

Early in the research it was decided that during the 30 month length of the project two mowers were measured monthly to identify possible degradation in the measurement methods used. This revealed that there is indeed a deviation taking place and that the repeatability of the test method needs to be studied further.

- **WP2** is dedicated to psycho-acoustic (sound quality) issues. The objective is to set up appropriate noise annoyance indicators for lawnmowers and to analyse correlation with sound emission in terms of dB(A). This has been done by sound quality measurements in operating conditions on a panel of products, assessment and analysis in terms of existing metrics (use of commercial psycho-acoustic software) and the development of dedicated lawnmower psycho-acoustic criteria.

  Although being an original and promising issue, this work package represents less than 20% of the total project.

  Preliminary results: Early on it was recognized that an evaluation had to take place of the degree of noise annoyance by different panels, private users, professional users, experts and engineers, and “neighbour type people.” Further the definition of novel sound quality metrics relevant for product quality appreciation and/or annoyance was established. Three voting criteria were used to determine the more annoying sound observed: “A”, “B”, or “Neither”.

  The results of the first type of jury tests showed that the “Paired comparison” proved efficient in ranking the machines according to one criterion but cumbersome to perform. “Differential semantic” proved handy to explore several subjective sound perceptions but difficult to prepare [5]. All the lawnmowers cannot be put into one “paired comparison” test; they are to be judged by family. “Differential semantic” tests will then unify the families around few subjective aspects of sound. See Figure 2.

	Not Acceptable
TORO-AP-03A	7.857
ALKO-AP-01	6.429
MTD-AP-04A	6.190
ALKO-AP-01A	5.714
TORO-AP-02A	5.238
JD-AP-02A	5.000
TORO-AP-01B	4.286
EL-AP-03A	4.286
TORO-AP-01A	4.048
MTD-AP-03A	3.810

	Loudness (Sone)
TORO-AP-03A	131.8
MTD-AP-04A	103.3
ALKO-AP-01A	84.5
ALKO-AP-01	82.8
JD-AP-02A	79.1
MTD-AP-03A	78.3
EL-AP-03A	76.2
TORO-AP-02A	71.8
TORO-AP-01B	71.6
TORO-AP-01A	66.9

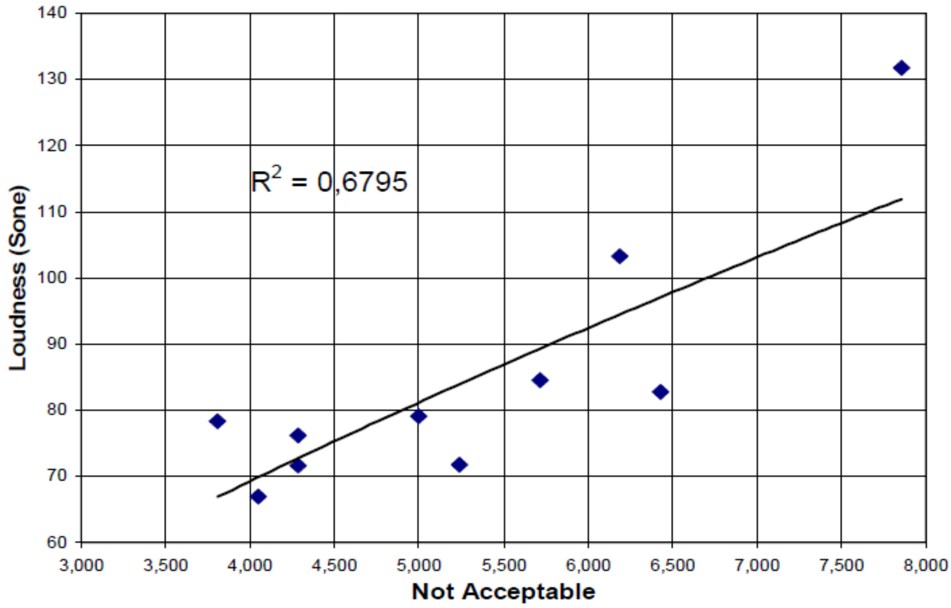

Figure 2: *Type of results - Differential Semantic*

- **WP3** deals with the blade as a source of noise. The aim is to reduce the noise by improved design, to establish links between noise and performance indicators (quality of cut, energy consumption, etc.) and to create a blade noise database. The basic tool has been a blade noise test rig, but a strong emphasis has also been placed on numerical computation methods and aerodynamic blade modelling.

  Preliminary results: 34 blades from 32 rotary lawnmower types were tested on a test bench. See figure 3. Blade diameters tested ranged from 371 mm to 817 mm. See Figure 4. An empirical model of blade noise was defined. The main contribution is broad band noise. The level of that noise is directly related to parameters affecting the blade efficiency; i.e. the ability of the blade to generate enough suction to transport the grass clippings. The ability to predict the trailing edge noise requires more investigation. At fixed tip speed, no significant influence of blade diameter has been found. As mentioned above the blade noise has proven to be the dominant factor in the sound power produced by rotary lawnmowers not yet taking into account the blade's interference with the deck structure as this adds to the equation. See Figure 5.

Figure 3: Blade test bench with *10 microphones on a 1/2 sphere of radius 1 m*

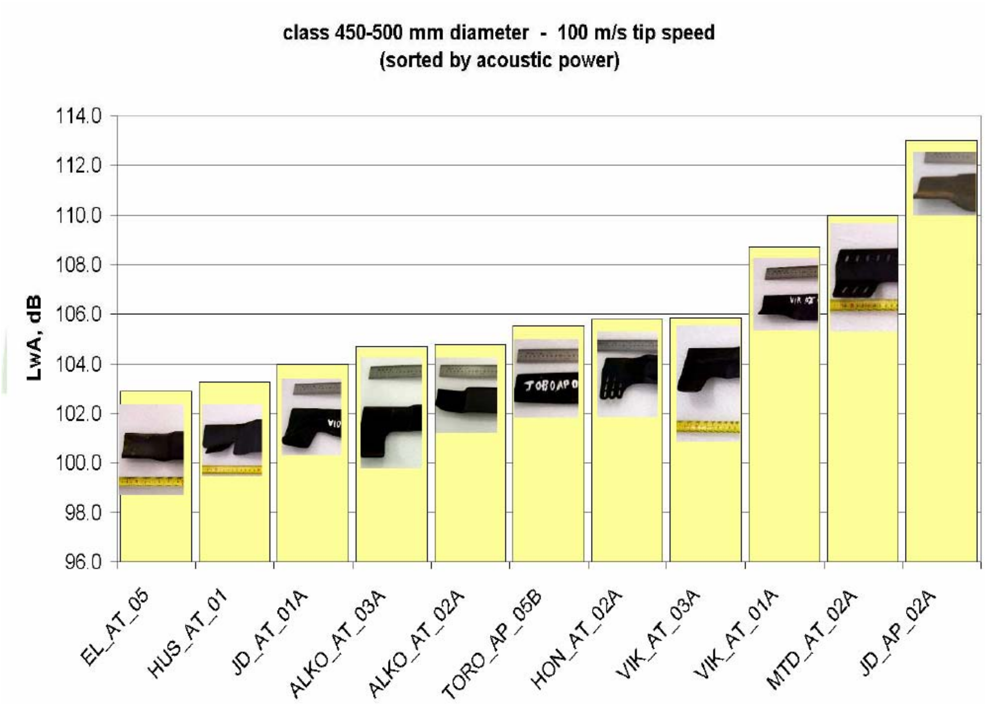

Figure 4: H*ierarchy selection of blades and wing configuration*

Blade noise varies with tip speed. A 10% increase in speed results in +1.9 dB(A) for a diameter 400 mm blade and +2.7 dB(A) for a blade diameter of 650 mm. Cross sectional area trailing edge vortices can increase blade noise in a significant way.

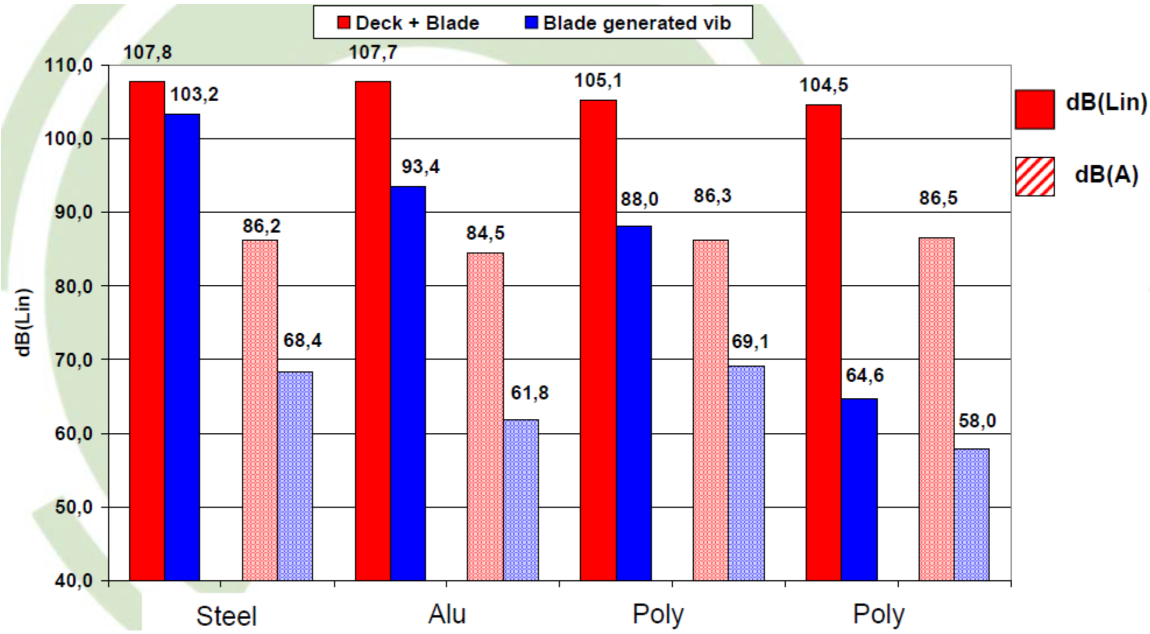

Figure 5: *Influence of the blade rotation to structure borne deck noise*

- **WP4** covers noise and vibrations generated by the lawnmower engines. Appropriate test rigs and measurement methods have been set up in order to analyse engine performance and its links with noise and vibrations, as well as with assembling and mounting technologies. It is also intended to create a database to be used in the virtual noise synthesis.

  Preliminary results: All aspects of engine noise have been evaluated. The aim of the project was not to look into the noise of the engine but to characterize the noise to develop data to be used in the design tool PRONS.

  The sound radiated from the engine, together with noise from the fan and intake has been classed as airborne (AB) sound. Secondly, when connected to the lawnmower frame, the vibrating engine may transmit vibrations to the frame which subsequently radiates structure-borne (SB) sound. Research has shown that although the engine and its components, see figure 6, appear to be the dominating factor in the overall sound of the rotary lawnmower this has proven not to be the case.

  Presently, engine manufacturers produce and/or supply engines for rotary lawnmower manufacturers that have sufficiently low exhaust muffler sound, air borne sound, and structure borne sound. These noise components are therefore of a lower priority than the blade noise. However the perception factor of the total engine noise component could give the impression that the engine seems to be the loudest.

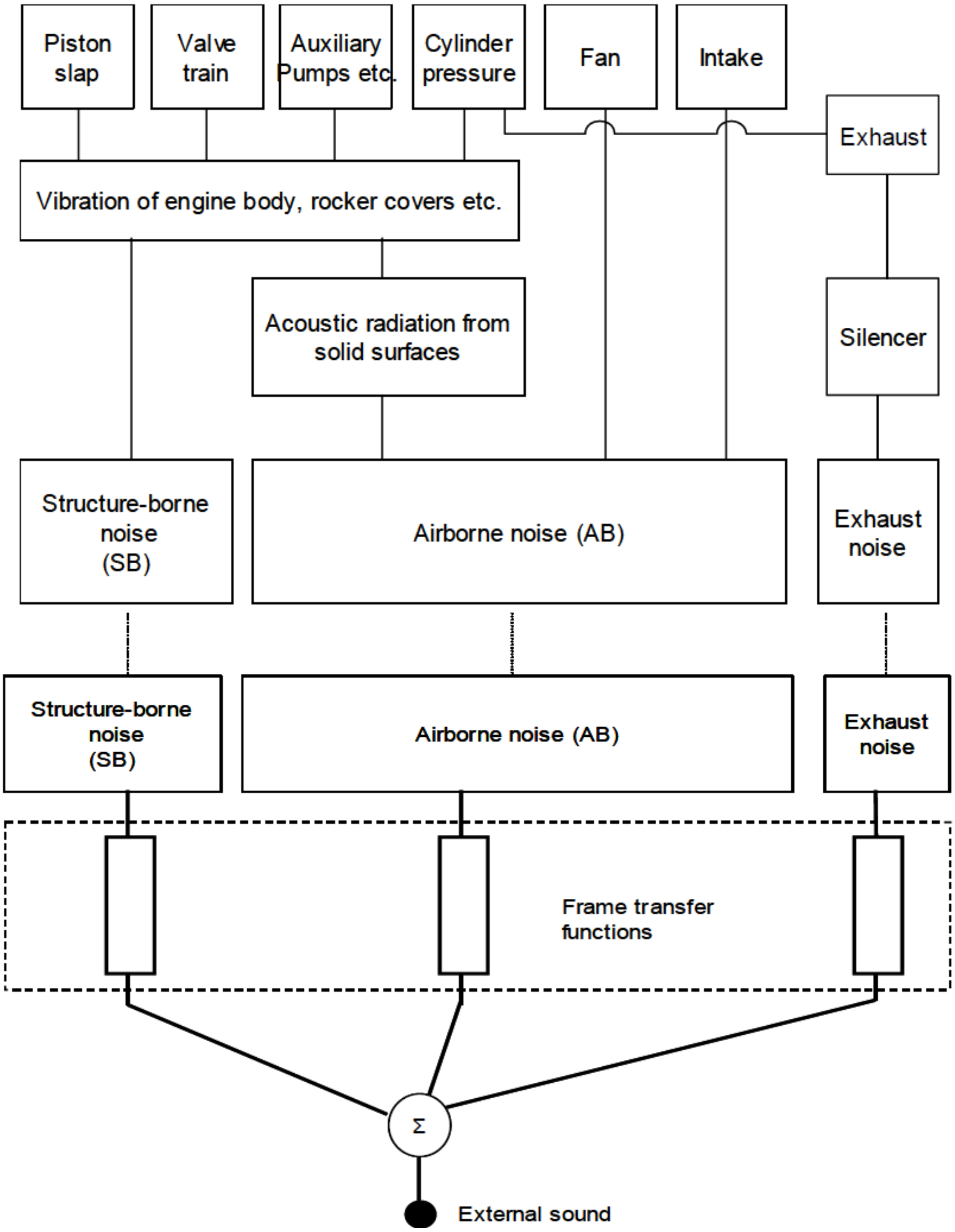

Figure 6: *Schematic of the individual engine sound sources*

A typical example in figure 7 of the frequency spectrum generated by a ride-on lawnmower front mounted engine fitted on the frame:

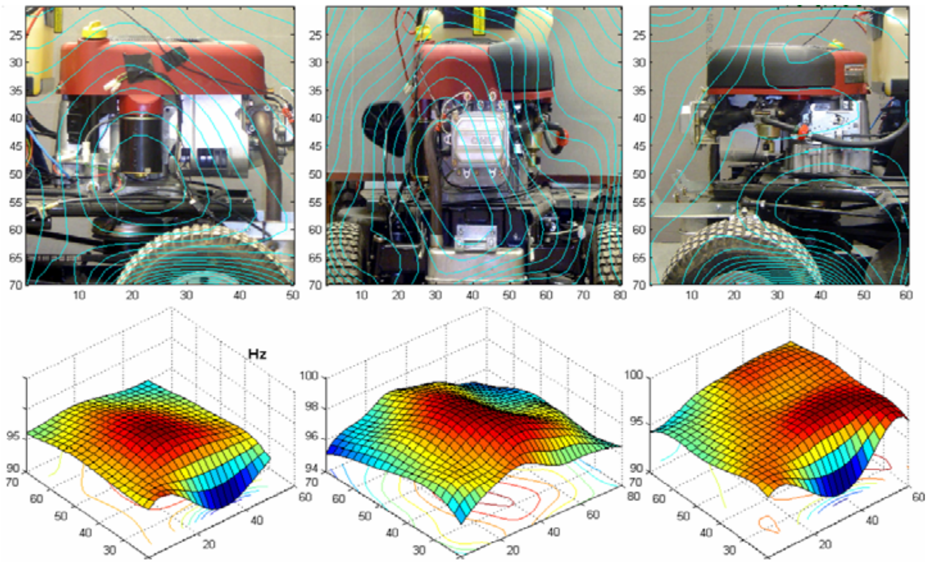

Figure 7: *Engine side view frequency spectrum*

- **WP5** is the third component oriented work package; it deals with noise and vibrations of power transmission components. An approach mainly by experimentation will allow characterising different components, to develop source-ranking techniques and to work out design rules for quieter transmissions.

  Preliminary results: In the lawnmowers, the transmission noise can be created by several components:
  - The belt-pulley unit,
  - The hydraulic transmission,
  - The mechanical transmission,
  - The coupling device (excluding the clutch),
  - The bearing noise (usually negligible unless a default appears).

  The most common transmission type among the studied lawnmowers is the belt-driven transmission, which is then further analyzed. Different kinds of belts can be found in industrial equipment:
  - Timing (or cog) belts,
  - V-belts (trapezoidal belts) or V-ribbed belts,
  - Flat belts.

  All the various belt configurations were tested and it was found as is shown in the figure 8 that the noise created by the various belt systems was generally lower in the overall ranking in comparison with the engine and the blade. The whole transmission system was therefore characterised as a “black box” for use in the PRONS design tool.

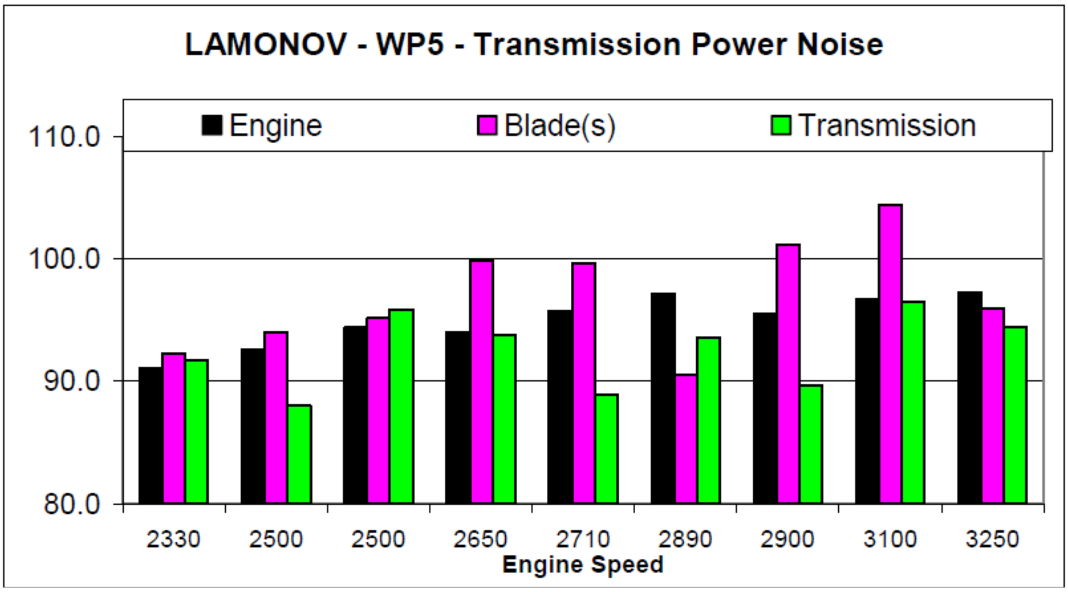

Figure 8: *Sound source distribution versus engine speed*

- **WP6** deals with acoustic "virtual prototyping" and re-design. Based on input of knowledge and data developed in WP3 to 5 it is intended to set up and to apply models using PRONS software package and to make noise assessments on chosen lawnmowers by using the virtual prototyping approach. In addition, training sessions for design engineers have been held on the application of developed techniques and software.

  Preliminary results:

  The PRONS software package needs time data or spectra as input. These data could derive from measurements or simulations. The terminus "virtual prototype" could be described with an example: The parts of an existing lawnmower (i.e., an existing prototype) have been measured and inserted in a PRONS model. The data of a component (e.g., the blade) could be filtered, replaced by the data of another lawnmower blade or by simulated data. PRONS will then synthesise the sound of the new resulting machine that does not exist as real assembled hardware and is therefore called virtual prototype. What is important in using this kind of software is the relative difference between two design solutions.

  Through Figures 9 and 10 one can get an impression on the various components that can be altered in the PRONS software and that could generate a relative difference so that a choice can be made for a specific design.

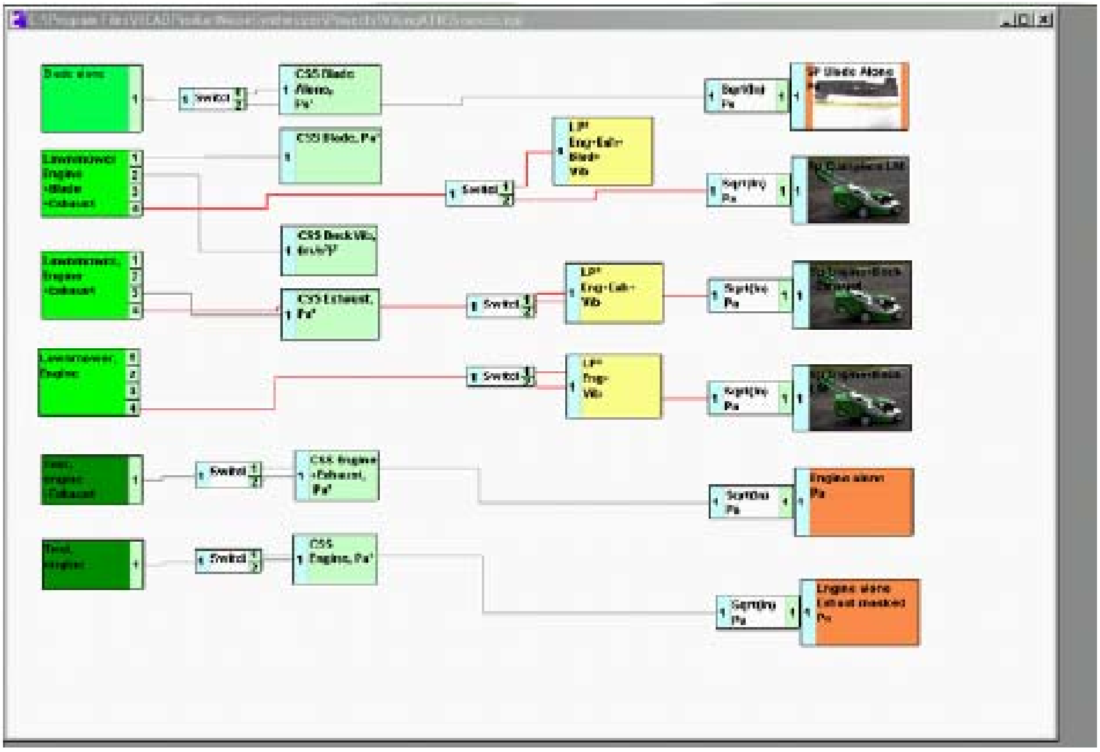

Figure 9: *Typical PRONS screen for a walk behind lawnmower showing the individual noise components*

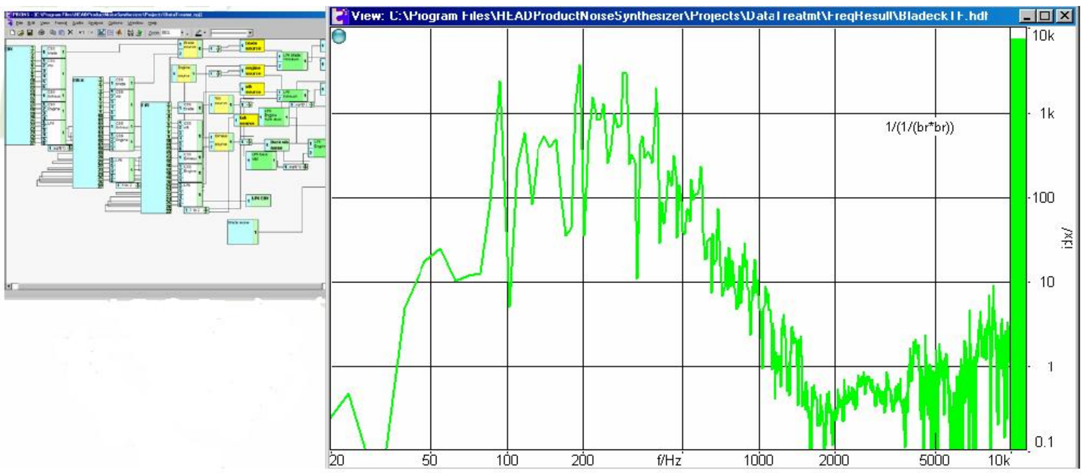

Figure 10: *Typical break out frequency spectrum screen within PRONS*

CONCLUSIONS

Never before has there been a research project on the lawnmower noise characteristics with such scientific detail as in LaMoNoV. Although at individual manufacturers level scientific proprietary research has been carried out in the last 25 years since the European Union regulations came into force, the present lawnmower configuration in comparison with lawnmowers produced over this 25 year period is the factual proof. This proprietary information could not be chaired with the authorities or with the European Gardenmachinery Industry Manufacturers Federation members. The obtained scientific data in LaMoNoV, although proprietary to the consortium members, can now for the first time be used in our contacts with the legislators. Furthermore the consortium members' staffs have been able over the past 30 months to communicate with the scientists who carried out this project on essential noise aspects of rotary lawnmowers.

The preliminary results have shown that certain aspects of the noise components can be better evaluated and possibly redesigned to achieve the present stage one limits without jeopardizing the demands the users of these products have on the performance and the "Quality Of Cut" (QOC). This has been one of the main concerns of the manufacturers of these products in order to maintain their market presence and at the same time adhere to the stringent stage one limits as laid down by the European Union and its member states.

The interaction of the blade noise with the deck structure is a complicated subject, despite the scientific data obtained; this project has shown that further detailed study is needed. Specifically in relation with the QOC this subject has proven to be a motivation for additional research. The preliminary results of the first QOC tests done show that the present reduction in blade tip speed has an important adverse effect on the QOC, confirming that other actions, based on more complex, and to be determined design changes, are needed in order to reduce the noise.

The "virtual prototyping" PRONS software has been judged to be a useful tool for further investigation at manufacturers' level into the various noise aspects of the rotary lawnmowers they produce or are going to produce. However time is needed to apply this design tool into the various research and development divisions of those companies and actual products will need several years of development before they could reach the marketplace.
In the meantime the project findings clearly show that the db(A) limit reduction required have had their longest time. Sound quality could prove to be the next step in altering the perception of rotary lawnmower sound. Additional study in the methods to be used is needed in order to make this a viable option.

The preliminary results of the research have shown that the physics of blade noise have reached the maximum level of noise limit reduction of rotary lawnmowers. In practice this means that further reduction is difficult through the present method used without affecting the user in his expectations and application of the rotary lawnmower. Additional evaluation is needed of the results of this research project in order to obtain the maximum advantage for the consortium members and to have a possible affect on the future design of their lawnmowers.

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