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RESEARCH AND DEVELOPMENT IN ACOUSTICS FOR PRACTICAL SOUND CONTROL ENGINEERING

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Abstract
Due to the pleasance and relevance listening to sounds may have, the investigation and targeted application of acoustic principles has been a constitutive element of natural science and technology since the earliest times. Starting from enjoyable sounds and communication once, the glut of today's unwanted sounds as well as the unlimited availability of specially generated, wanted sounds have turned acoustics into an indispensable element of modern technology. This has been strongly pushed forward by the need for well-aimed control of unwanted, annoying or even health affecting sounds and vibrations as inherently generated by our progressively mechanised world. Thus, practical noise control engineering has strongly contributed to and benefited from any progress in the field of acoustics. And, to meet future challenges, effective noise control engineering will continue to stimulate as well as to crucially depend on further progress in acoustics.
The lecture demonstrates how research on noise effects helps to identify problems, how such problems then provoke better insight and methodological approaches and, finally, how any related acoustic progress then leads to innovative solutions in practical noise control. To further highlight the importance of research and development in acoustics for practical noise control engineering, recent fields of interest will be presented and discussed in some detail: the capabilities of experimental modelling in transfer path analysis and synthesis, the conceptive impact of modelling rolling noise generation, the great potential of consequent application of acoustic principles to silent road surface design and the innovative perspectives of active sound control.

Keywords: engineering acoustics, sound control engineering, transfer path analysis, road tyre noise, low noise road surfaces, active control of sound and vibration, active sound design.

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1 Introduction

The world is full - and fills up more and more - with sound. This is the natural but mainly undesired, "noisy" result of our continuous efforts to subjugate our world by technical means. But that's not enough: As if sound were addictive, we more and more embed our life into sounds, cut even off ourselves by devoting our ears to numerous loudspeakers and individual headsets. Sounds may please or threaten us, may bring us good humor and optimism or, on the other hand, may drive us to despair, may bring us serious sickness. In any way we may state that sound, being used and suffered that extensively, must be a major field of interest and concern to us.

This is not equally true for acoustics, the science of sound, as part of physics. Although being part of serious research efforts since the times of the Ancient World, it was unimaginable in the 19th century even that acoustics might gain the all-day relevance it has today. Later, in the first half of the 20th century, apart from this persistent applicative underestimation, acoustics also lacked the theoretical attractiveness of other, more “fashionable” physical disciplines. This was mainly due to the fact that acoustics was well understood and had been comprehensively described in the second half of the 19th century. Best known examples are the works of Hermann von Helmholtz and Lord Rayleigh ([1],[2]).
This didn’t change too much when acoustics started to enter the domain of engineering. Being caused by the many successes in electro acoustics as well as by the upcoming annoyance of people affected by noise, scientific interest in acoustics got fresh impetus from the formulation of technical problems in the first half of the 20th century. Then, after the many devastations of World War II, it was the rapidity, cheapness and the resulting, unsatisfactory quality of reconstruction which raised wide awareness for acoustic quality. The “economic miracle” together with growing prosperity and demands naturally focused on the discomfort of noise and thus established noise control and acoustic quality as valuable, even necessary technical targets ([3]).
Consequently, after having focused more and more on technical acoustics between 1900 and 1950, the focus of the second half of the 20th century turned to engineering acoustics, the acoustics needed by the engineers.
Today, the unlimited availability of wanted and - above all - the sorrowful, intolerable glut of un-wanted sounds has turned acoustics into an indispensable element of modern technology in both, aiming for environmental compatibility as well as for convenience, acoustic comfort. As both these aims are most relevant for the long-term acceptance of modern high technology, they are relevant parts of such high technology itself.
Of course, this relevance of technical and engineering acoustics has revived acoustics as a whole, has initiated many new research and development activities and thus - in an iterative procedure - contributed to and benefited from progress in the wide field of acoustics. So the stimulus started from acoustic claims to modern technology has promoted acoustics to become an important part of applied science again which - by its most interdisciplinary character – is crucially linked up with nearly all technological disciplines and thus became a highly needed, essential part of today’s technology and science. This is what this paper is dealing with - to identify and to illustrate the mechanism of interdependence and mutual influence between research and development as driven by and for practical, i.e. applied sound control engineering.

2 Iterative cycle of research and development

As long as practical engineering tasks and solutions are involved, the interplay between research and development is not driven for its own sake. Instead it typically follows practical needs and technical possibilities. Therefore, any practice oriented cycle of research and development involves technical realizability and practical applicability.
Fig. 1 illustrates schematically this cyclic procedure which also defines the interactive role of engineering acoustics ([3]). Starting from direct contributions to research, engineering acoustics can help to

- develop concepts and solutions, then to
- technically implement these to solve practical acoustic problems, to
- apply the technical solutions to reality and finally – by assessing its success – to
- formulate the need for improvements or new approaches which should be a matter of research again and thus finishes the closed cycle loop.

It was this ongoing procedure which maintained progress and success of engineering acoustics from the mid of the 20th century to these days and which thus initiated the recapture of acoustics from a basic and well-established discipline of physics to a highly topical discipline of modern technology. To illustrate this, we will focus on three obvious and representative examples. The selection of these examples is driven by the intention to focus on typical, frequently recurring elements of the iterative procedure which also describe the general roles and interconnection of research and development.

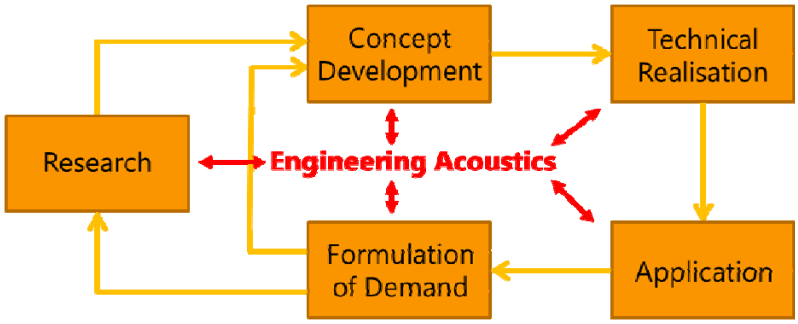

Figure 1 – Iterative cycle of research and development involving implementation and application.

To be able to follow reasonable targets with predictable results, research and development (R&D) make frequent use of models to simulate and predict the effect of R&D results. A reliable model covering the scope of the approaches to be applied and providing quantitative predictions of their effects is the best guarantee for having understood all mechanisms involved. And this understanding is crucial for effective design, development, realization and application of any practical sound control approach. For this reason we will emphasize the relevance of modelling and simulation and give some general clues for practicable and effective modelling in acoustics.

The first example given in section 3 is taken from the experimental domain where specific measurements shall provide parameters of a system to be investigated and identified. If successfully done and evaluated, these parameters give relevant information on the system's characteristics up to a partial or complete model of the system. A specific approach to model the sources of a system and to quantify their contribution to a target field quantity by measurement is transfer path analysis (TPA). TPA follows a particular approach which allows to further split these contributions along various propagation paths.

A most recent example of interaction between a powerful model and practical noise control solutions is the successful reduction of road/tyre noise by low noise road surface designs. Such designs must be reliable to justify expensive road construction works and the respective reliability crucially depends on the availability of appropriate models. Section 4 will shortly describe the approach and highlight some successful applications of low road noise implementations together with the resulting technological state of the art.

Finally, an overview of recent research and development in acoustics should not skip one of the most fascinating concepts which was subject of many hopes and some technical dreams over the last decades: the concept of active control of sound and vibration where new coherent (secondary) fields are generated, controlled and superimposed to interfere with a given (primary) field. To make this interfering secondary field quantities match the given primary ones, the controller must know in advance how his output is transmitted to the interfering point. This means that the controller needs a model of this secondary path. Again, a model is needed and if necessary, this model must be updated regularly to follow eventual changes in this transfer behavior. Section 5 will summarize the development of active noise control (ANC) and active sound design (ASD) and give an assessment for practical applications of the technology.

Altogether, apart from illustrating the interaction of research and development, the role and relevance of modelling will be highlighted exemplary in each of three phases, analysis, design and implementation of sound control measures.

3 Transfer path analysis

The basic concept of transfer path analysis was established and introduced around the middle of the second half of the last century when digital technology started to allow for new signal processing approaches. The resulting possibility to easily evaluate mechanical point and transfer mobilities opened the floor for concrete characterizations of sources and transfer functions. It was just natural then to try to identify mechanical systems in terms of sources and propagation/transfer paths and thus, the principle of transfer path analysis had been launched. Following the detailed description in [4], this principle will shortly be reviewed.

The basic idea was to identify - for a given point of interest - the relevant set of sound or vibration sources together with a relevant set of propagation paths from these sources to the point of interest. Fig.2 gives a schematic illustration.

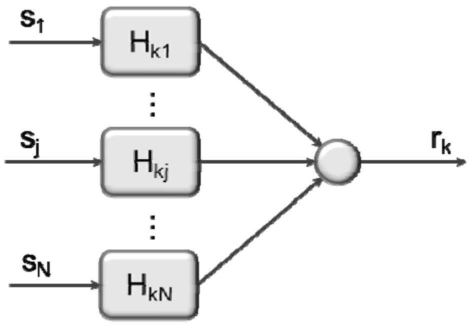

Figure 2 – Principal sketch of sources contributing to sound and vibration at the receiving point of interest via allocated transfer functions.

If the sources s_j ($1 \leq j \leq N$) acting on a system H and the transfer functions H_{kj} ($1 \leq k \leq M$) describing the effect of the sources s_j to a receiving point r_k both are known, a simple linear model of the structure and its excitation has been found. In particular, this model will be able to quantify the contributions from each of the sources and to further identify to what extent the respective transfer paths contribute to the field in the receiving point r_k. The composition of thus determined partial contributions to the total field quantity r_k is referred to as transfer path synthesis (TPS),

By comparison of the synthesized signal with the original signal obtained from measurement a first validation of the TPS can be obtained. If - in addition - more parameters of the field quantities and the corresponding systems are known, e.g. input and output impedances of the sources and the transfer paths or all four-pole descriptors, the model can even be used for modification analysis. Then the effects of applying alternative force distributions or modified transmission paths can be investigated by applying them to the model. However, such detailed knowledge of the model parameters requires essential efforts which typically, i.e. under normal laboratory situations are not available.

Therefore, the technical development of transfer path analysis was continuously driven towards simplified approaches which more and more gave up the prospects of system modelling for modification synthesis to the benefit of simple analysis by straight forward measurement procedures.

3.1 Basic concepts

Seen from the perspective of linear system theory, the problem of finding a linear model between mechanical and acoustical input excitation and some resulting output field descriptors can be classified as a typical problem of system identification. Such models can be easily identified if the system is

observable with respect to the referred field quantities, i.e. if these field quantities are accessible to direct measurements.
For typical TPA applications such observation is rather unlikely or - if possible at all - obtained with high efforts only. This is because any measurement of operational forces between an exciting and a receiving structure requires force transducers to be placed there before. This is not only time consuming but also depends on the availability of sufficient installation volume.
For these reasons, TPA measurements in practice often prefer to be based on indirect force measurements where the operational forces acting on a structure are identified by some other, responsive field quantities. This can be expressed by the simplified scheme of fig. 3, where an intersection level with intermediate response "r_i" has been introduced between the excitation level "s" (source) and the final response level "r".

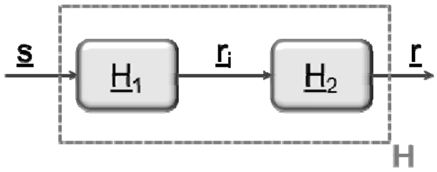

Figure 3 - Principal sketch of a TPA arrangement with intersection level for additional identification measurements.

Based on the partial transfer matrices H_1 and H_2, the quantities put together in the vectors $\underline{s}$, $\underline{r}_i$ and $\underline{r}$ can be related by the equations

$$\underline{r}_i = \underline{H}_1 \bullet \underline{s} \tag{1}$$

$$\underline{r} = \underline{H}_2 \bullet \underline{r}_i = \underline{H}_2 \bullet \underline{H}_1 \bullet \underline{s} = \underline{H} \bullet \underline{s} \tag{2}$$

Assuming that the intermediate quantities put together in the vector $\underline{r}_i$ are well correlated with the driving forces put together in the source vector $\underline{s}$, some inversion of the transfer matrix $\underline{H}_1$ will allow to identify the sources $\underline{s}$ from the observations $\underline{r}_i$.

$$\underline{s} = \underline{H}_1^{-1} \bullet r_i \tag{3}$$

As illustrated in fig.4, this indirect estimation of the driving sources from some intermediate response is referred to as matrix inversion method.

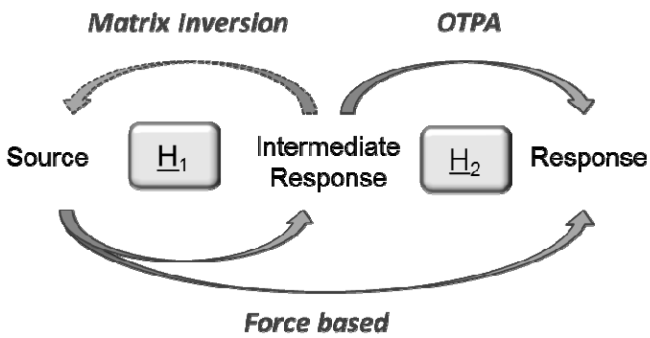

Figure 4 - Illustration of methodological approaches being included in the structural scheme of fig.3

Apart from formally describing the method of indirect excitation measurements, the structural diagram of fig.3 covers additional modifications of the TPA approach. Based on a TPA related contribution analysis from the sources $\underline{s}$ via $\underline{H}$ to the receiving points $\underline{r}$ (see lower “force based” arrow in fig.4), additional measurements of the intermediate quantities $\underline{r}_i$ may allow to further resolve the contributions along the paths defined by the positions of the intermediate quantities $\underline{r}_i$ (see upper left “force based” and “OTPA” arrows in fig.4). This means that serial TPA arrangements may refine the resolution of a single TPA by further identifying partial contributions according to their respective transmission paths.
Finally, figures 3 resp. 4 include an arrangement where the restriction to measurements of the received signals $\underline{r}_i$ and $\underline{r}$ abandons any determination of operational sources $\underline{s}$ by directly extracting transfer information from the transfer functions of matrix $\underline{H}_2$. This approach is called operational transfer path analysis (OTPA, see respective arrow in firg.4). Although the classification “operational” in a strict sense might apply to all TPA approaches where the analysis is based on operational field quantities (measured “in operation”) only, the term “operational transfer path analysis” commonly refers to the particular case where the identification of transfer functions is based on operational signals only. This characterization makes a clear distinction to all approaches where these transfer functions are obtained from separate, non-operational “off line” measurements.
To make a further distinction between the transfer functions of $\underline{H}_2$ relating driven, received signals only and the transfer functions of $\underline{H}_1$ relating received to physically really driving sources, the elements of the second, $\underline{H}_2$, often are referred to as transmissibilities.

3.2 Methodological approaches to TPA / TPS

Among various approaches how to carry out TPA in detail four methods have found some continuous interest of acoustic engineers and thus are used regularly for vibroacoustic analyses. They principally differ in that three of them use explicit direct measurements of the transfer functions of interest while the forth uses an estimate of the transfer function obtained from operational data only. It may be obvious, of course, to do a specific measurement if these transfer functions have to be determined. However, in many cases this can require high efforts if the excitation points are not easily accessible or if they are loaded by connected structures. In view of the efforts needed to disconnect the exciting source side from the excitation inputs of the receiving structure, operational measurements get highly attractive even if they give up parts of the information.
Once the transfer functions are given, the remaining task is to determine the exciting field quantities. As these are thought to describe the investigated system in operation, they have to be operational data. With the preliminary restriction to vibroacoustic transfer functions, these quantities are the operational forces being effective at their inputs. The methods following up this procedure are referred to as force based methods. They differ in the way they evaluate the forces of interest. Apart from measuring these directly by force sensors (direct force method), they may be evaluated indirectly from measurements of the relative displacements of elastic mounts (mount stiffness method) or from intermediate responses (see fig.4) by matrix inversion (matrix inversion method).
All these force based methods differ by principle from operational transfer path analysis (OTPA) which abandons the explicit determination of transfer functions and forces in favor of easily obtained but useful estimates. Although being the most natural TPA approach which generally leads to the best results, force based methods require substantial efforts to determine both, the transfer functions and the excitations acting on them. For this reason engineering inventiveness has been concentrating on finding better compromises between experimental effort and informational content of the results. From the procedural point of view the most promising approach was seen in giving up complicated access to the excitation points and using easily accessible measurement points only. Following up this consequently by neglecting any registration of the driving forces at all, the remaining concept for system identification is in agreement with the simplified approach being referred to as OTPA ([5]).

3.3 Analysis and design modelling

By following the various approaches to TPA it could be observed that ongoing simplifications were related with some losses in using the resulting model for predicting the effects of modifications. In the early days, the idea of TPA was strongly driven by obtaining an experimental model which then allows for modifications of its elements. Such a model then would be able to predict the effects of modifications in excitation and construction. However, to integrate changed components like alternative sources (engines) or modified transfer paths into an existing model, precise knowledge of the coupling characteristics is required.

These characteristics may be given in terms of four-pole descriptors or, on a lower level, in terms of some input- and cross impedances/mobilities at least. Together with the components of TPA analysis they then may serve as a basis for a parametric model which can be and has been used to investigate the effects of constructional modifications by changing the parameters appropriately. Further to this, such empirical models were also chosen to be used in combination with purely numerical (e.g. FEM) simulations. Such simulations then could concentrate their computing efforts on modelling the most relevant parts of a system while being sure that the surrounding system components were modelled close to reality.

However, after some initial enthusiasm, the great efforts needed to determine this complete set of parameters withstood the wide acceptance and dissemination of this modelling concept. Instead, limitations in use were accepted to the benefit of easy-to-implement and -apply approaches. The related simplifications successively followed the scheme of approaches as outlined in the previous sections and it is obvious that reducing the information to be deduced from measurements reduces the interpretability and modelling capabilities of their results.

Thus, the high simulative flexibility of a thorough TPA based on transfer- and cross accelerances as well as on input impedances of the receiving and output impedances of the source structure was more and more given up and ended in allowing slight simulative changes only for slightly modified OTPA components.

However, OTPA did not essentially affect the analyzing capabilities of the TPA approach. By allowing fast repetitive measurements instead, simulative comparisons could easily be replaced by experimental verifications of differing problem solutions ([6]). As an example how OTPA may be used to analyze different contributions to a given sound, a typical result of pass-by-noise contribution analysis will be presented in the next section.

3.4 Pass by noise contribution analysis

Being the most relevant and standardized procedure to officially characterize the noise emission of automotive vehicles, pass-by measurements play a significant role in designing cars. To be able to keep the effort for repeated real pass-by test measurements within manageable limits, they are generally substituted by simulated pass-by measurements in laboratory environments. Replacing the moving position of the car by delaying the outputs of a line of microphones accordingly, pass-by characteristic sound signals are obtained.

If these signals are to be subjected to a transfer path analysis, the “moving” transfer functions between source and receiver signals can be determined from a set of simultaneously measured transfer functions between fixed measurement points.

Fig.5 shows a typical arrangement where the line of pass-by microphones can be seen in the background together with some of the source reference sensors in the foreground. In particular, two microphones for each tyre, one in a lead and one other in a tail position, can be identified. In this experiment, the remaining set of source reference sensors was given by a total of 5 microphones for the engine compartment, 2 microphones for the exhaust pipe system and 1 microphone for the air intake.

Pass-by was simulated by 30 microphones placed in 1m distance from each other on each side of the rolling test bed.

Figure 5 – Test arrangement for pass-by related OTPA measurements.

Fig.6 gives exemplary results obtained from operational transfer path analysis of 3rd gear accelerated path-by noise ([7]). In fig.6a (left) the total sound pressure given is the result of summing up the individual contributions. This calculated result closely matched with test measurements. It can be seen that the total sound pressure increases if the car is approaching (-10 to -2 m), then takes a lower value and increases again (-2 to +9 m) and finally starts to run out (> 9 m). The fluctuation is mainly caused by the contribution of wheels, thus showing that rolling noise is the dominant pass-by noise source. Only engine noise has a visible influence on the total noise by increasing the difference between total noise and wheel noise from - 2 to + 5 m.

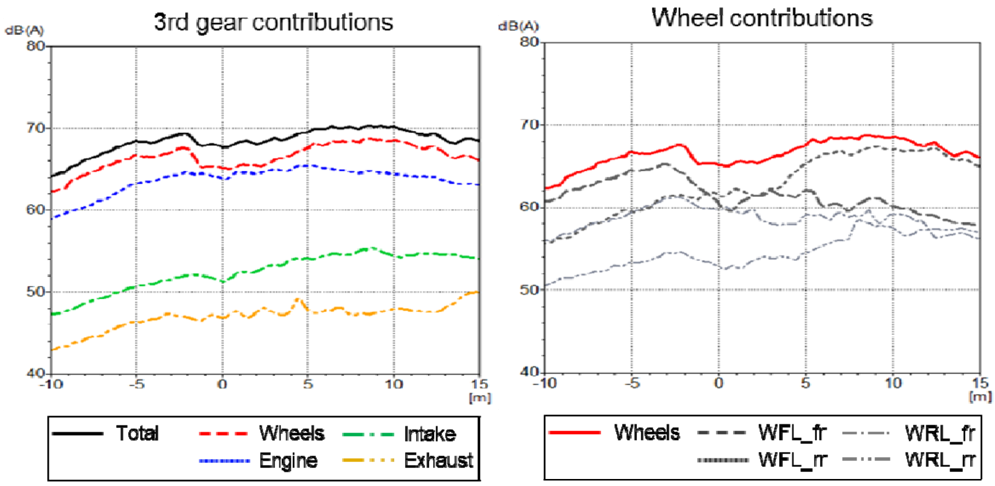

Figure 6 – Results of pass-by noise contribution analysis for major noise sources as a function of simulated car distance (a, left) and results of wheel/tyre pass-by noise contribution analysis as a function of simulated car distance (b, right).

Fig.6b gives further insight to the rolling noise contributions from the tyre as registered by the two microphones in lead and tail positions. It can be seen that forward radiation (lead microphone WFL_fr) of the front tyre is dominant while the car approaches (-10 to -2 m) but is replaced by backward radiation of the front tyre (tail microphone WFL_rr) while the front wheel passes by (-2 to +15 m). The rear tyre components do not significantly contribute because the test car was full load front-wheel driven. Apart from illustrating the relevance of effective sources, contribution analysis thus may indicate very specific noise control measures to modify and limit the contributions and the resulting total noise level.

3.5 Transfer path analysis - Summary

Continuous refinement of the basic TPA approach over the last decades has been able to broaden the spectrum of implementations and to consolidate the method as a constituent part of today's engineering toolbox. Transfer path analysis can be seen as a sophisticated strategy for well-aimed multi-channel measurements typically following physical, source- and propagation-based insight. However, the success of the approach depends on the skills of the conceptualizing engineer in defining measurement points and evaluation strategies.
Initially being designed for experimental modelling purposes TPA gradually changed its focus because of unacceptable efforts in practice. Thus, reduced modelling capabilities were accepted on account of essentially reduced measurement duration. Also, new, improved evaluation concepts helped to increase the accuracy while reducing measurement and evaluation efforts. All in all it can be seen that the interactive interplay of research, development, implementation and application changed the focus of TPA to better meet the analyzing needs of engineering practice.

4 Road Tyre Noise

4.1 Modelling road tyre noise

Generally, rolling tyres on roads generate sound by two generating mechanisms. Mechanical rolling excitation causes radial and tangential vibrations of the tyre which may be radiated as sound (<u>mechanical excitation</u>). Also, the surrounding air may be excited by inclusion, compression and release of the air in the contact patch (<u>aerodynamic excitation</u>, air pumping). Today both mechanisms are agreed and well understood.
However, the total sound generated by rolling tyres also crucially depends on the radiation impedance seen by the sound sources. Here, the horn effect related to the growing distance between tyre and road is of particular relevance. Involving acoustic characteristics of the road, this radiation impedance is an important key to noise control measures by road design.
So there are basically two approaches to control the noise which is generated from the interaction between the rolling tyre and the road: changing relevant characteristics of the tyre or of the road. But whatever design changes are considered, there effects on rolling noise generation can only be assessed by experiments or by understanding the mechanisms in detail, i.e. by an appropriate model.
Here, appropriate means that this model should be as simple as possible or as complex as necessary. This is important because the model used to support the acoustic design engineer must allow interactive work to cope with engineering needs. Such interactivity requires and assumes handsome computation times which may not be achieved for complicated numerical methods of high computational effort. Inspite of enormous electronic progress this may be achieved only for simplified models where computations can be based on simple assumptions and relations. Such models typically justify themselves by providing useful results for whatever procedure these are used for, e.g. acoustic designs. And they typically may be obtained from a physical substitute model using a limited set of physical parameters.

A proven substitute model for rolling tyres is schematically shown in fig. 7. Basically, this model consists of a plate being supported elastically and being covered by another elastic layer. Mathematically the system of fig.7 can be described by a set of coupled partial differential equations depending on a set of physical parameters characterizing the elements involved. These parameters must be chosen such that the model outputs best match the outputs of the tyre to be modelled. Of course this plate-based parametric model is not capable to fully describe the vibrational behavior of a tyre. But it turns out that such a plate correctly describes the interaction between road and tyre and –equally important – the acoustic consequences of this interaction ([8]).

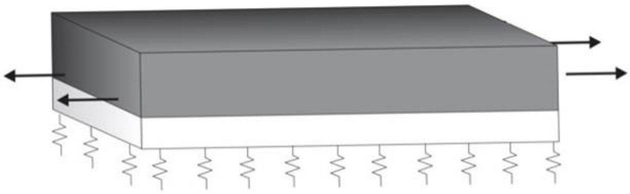

Figure 7 – Substitute plate model with elastic cover layer and elastic support as simplified model of a rolling tyre

This can be seen from fig.8 where the plate model is used as a constitutional part of a simplified non-linear contact model allowing the computational specification of the contact forces being effective between tyre and road. While the parameters of the tyre models must be evaluated from appropriate tyre measurements, the nonlinear stiffness being effective in the contact patch can be evaluated from road roughness and tyre profile. It should be noted that specifying the contact forces is exclusively left to calculations because there is no way of specifying them by measurements. The great practical value of this model based on contact forces may be seen from the fact that there is a linear relation between these contact forces and the road/tyre rolling noise related to them and that this linear relation can be identified by a statistical model, i.e. a model which can be derived from numerous measurements ([9]).

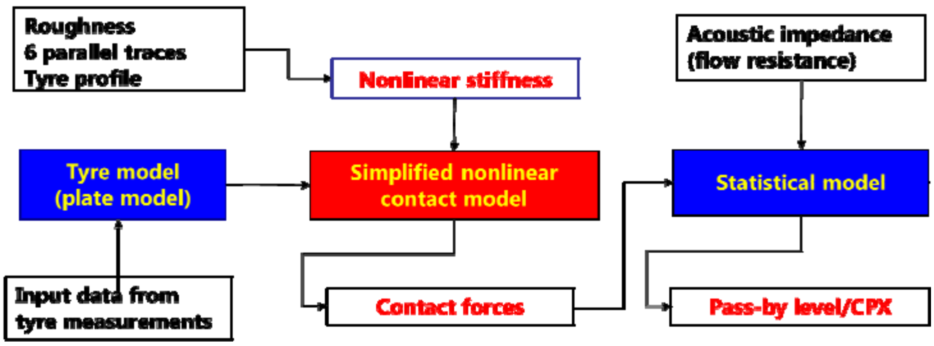

Figure 8 – Model for Statistical Physical Explanation of Rolling Noise (SPERoN) by combining the physical model to determine effective contact forces and the statistical model to further determine the respective rolling noise.

4.2 Low noise road surfaces

It can be seen form respective investigations that the potential for noise reduction by road surface design is essentially higher than for tyre design. Therefore it is worth to use the constructive design of road surfaces to reduce the noise generated from rolling tyres. Practical measures first concentrated on sound absorbing road surfaces. Unfortunately, inevitable dirt makes such open porous surfaces suffer regular losses of their absorptive performance which limits their lifetime. A remedy could be found by introducing two absorptive layers with an upper fine-grained layer (fig.9). While increasing the dirt resistance of the upper layer, the finer grains also increase the lifetime of these designs. Being realised with asphalt first, one- and two-layered open-porous asphalt (OPA, 2OPA) surfaces are widely used today and may be seen as state-of-the art solution for low noise road surface designs.

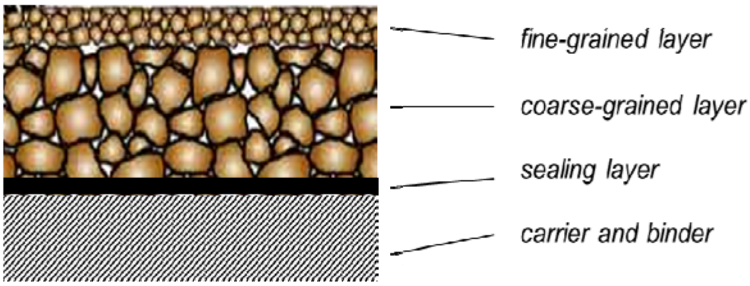

Figure 9 – Principal sketch of a two-layered open-porous absorbing surface

An example of the typical performance of such layers is given in fig. 10 which shows a level reduction of 6-7 dB ([10]) while crossing the 2OPA-layer. Generally it can be stated that 2-layered absorbing surfaces reach level reductions up to 8-9 dB. However, dirt typically decreases this noise reduction by 0.5 db per year. This strongly motivates research and development for improvements.

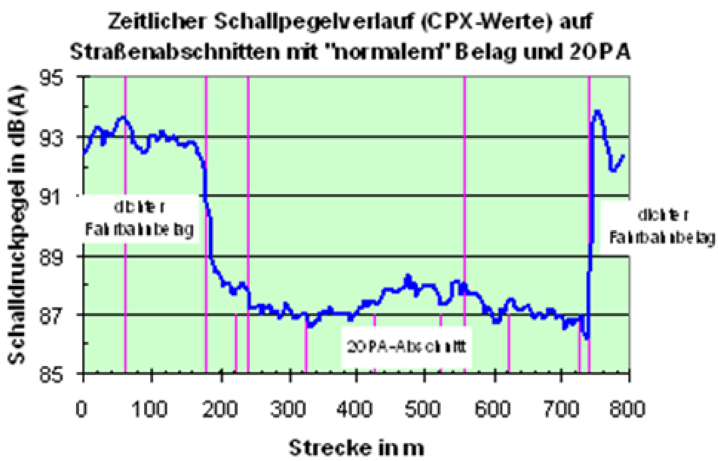

Figure 10 – Rolling noise level while passing over a 2-layered open-porous asphalt road surface (2OPA, CPX-measurement)

There are three approaches to realize such improvements in pactice: improving the absorptive performance of the layer, reducing the dirt risk by using materials of higher dirt resistance and focusing on minimizing mechanical excitation by using smooth surfaces.

The absorptive behaviour of 2-layered open-porous surfaces is characterized by two maxima whose position in the frequenca domain should be chosen by design such that they best fit typical traffic characterisitcs like average speed or dominant tyre (truck, passenger car) types. If the absorptive characteristics are to be optimized, it is obvious to try to make it more broadband by adding additional absorbers with additionally tunable frequencies. This is typically done by cavity resonator elements which can be tuned to specific frequencies ([11]).

Although this is a proven and widely used tool in acoustics, it is a demanding challenge to realize such resonators under the robust conditions of road construction works. Fig. 11 shows how such a cavity resonator may be accomplished by elements with various volumes and necks which then are integrated into an absorbing road surface layer. Fig. 12 shows the process of covering the cavity resonators by a porous asphalt layer. It is obvious that the respective road works need great care to preserve the sensitive structures and the resulting acoustic performance. However, if such care is successfully applied, an additional level reduction can be obtained. In the case of the example shown this additional reduction was 2-3 dB if compared to the same 2OPA layer without resonators ([11]).

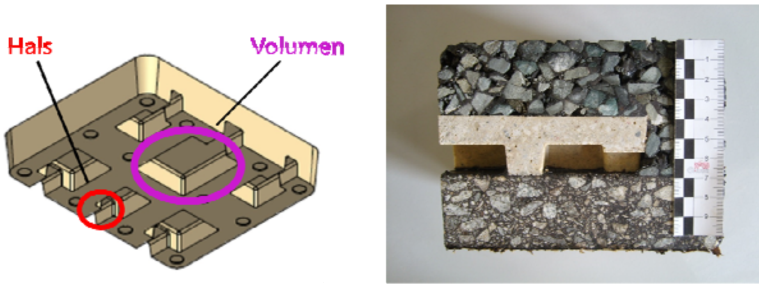

Figure 11 – Design and in-road-realization of a resonator with three differently tuned cavity resonators

Figure 12 – Process of covering cavity resonators by a porous asphalt road layer

A last example will illustrate the use of concrete as a material of lower dirt sensitivity together with the use of smooth surfaces to reduce mechanical tyre excitation. Both approaches can be easily implemented by using concrete pavements. Starting from the elements given in fig. 13 all design and constructive options were optimized with the SPERoN model. With these options level reductions of 4 dB for the dense surface and 7.6 dB for open-porous elements could be obtained ([12]).

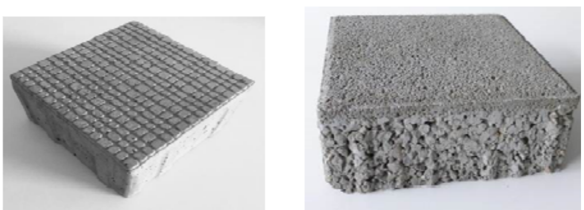

Figure 13 – Noise reducing concrete pavement elements with dense surface of optimized texture (left) and as open-porous absorbers (right)

4.3 Road Tyre Noise - Summary

As shown in the above sections, the development and availability of an interactive design tool based on a problem oriented hybrid (physical and statistical) model has enabled targeted designs of low noise road surfaces taking into account specific traffic parameters. With such designs it is possible to adapt the surface characteristics to specific needs and priorities (like reduction levels, dirt sensitivity, lifetime or cost). The iterative interaction of research, technological implementation and application thus was able to activate the potential of rolling noise reduction, to implement acoustic principles in the robust environment of road works and to obtain the technological readiness for market take-up.

5 Active control of sound and vibrations

5.1 Historical background and technology review

Starting from the very first formulation of controlling some given (primary) sound by superposing some other coherent (secondary) sound in the thirties of the last century ([13]), this technological approach of active sound control has fascinated generations of acousticians and noise control engineers. Today, after many phases of enthusiastic hopes and gushing confidence, a realistic assessment has gained wide acceptance.

This enthusiasm was likely to maintain exaggerated expectations which then - together with the thus raised promises - were able to initiate and find financial support for many non-coordinated research and development activities. Together with the fact that for many years the needs of active sound and vibration control were at the front of state of the art technology in digital signal processing and actuator design, this particular scenario has slowed down the process of focusing on the feasible. It thus took some 70 to 80 years to turn first hopes and dreams to clear conceptual and technical insight.

Starting from the above mentioned patent formulation of the basic concept, it took two decades to put these first ideas to first action ([14],[15]). Simple experiments mainly carried out in the US in the fifties gave first insight into practical aspects of implementing the approach by controlled interference. In spite all fascination practical difficulties with technical applications seemed to prevent concrete technological targets. At that time, this was mainly due to

- incomplete understanding of the physical possibilities
- complexity of the whole task
- restricted possibilities of analogue control technology
- efficiency limitations of sound actuators, particularly at low frequencies

Consequently, technology readiness levels obtained at that time were not to go beyond values of 4, “validation in laboratory environment”. For this reason, further research concentrated on particular theoretical and analytical considerations how to control the excitation and propagation of acoustical and vibrational wave fields.

It took until the seventies then that these considerations were picked up systematically in France and England first, then in the US and Germany. This finally resulted in comprehensive investigations on the general possibilities of active field control. With singular demonstrators being developed in parallel, technology readiness levels of up to 6, “prototype demonstration in relevant environment”, could be obtained ([14],[15]).

When the immense future possibilities of digital signal processing were to be expected, all existing fascination turned to euphoric hopes for the future. Extremely exaggerated confidence and optimism together with untenable promises caused high pressure to succeed for both, engineers and investors. The resulting hype together with a counterproductive patent euphoria prevented a clear and coordinated sequence of developments and thus hindered the realistic assessment of technological implementations. In the late eighties this consequently ended in disillusionment with respect to the method-

ology. Although sporadic demonstrators were able to obtain a technology readiness level of 7, "prototype demonstration in operational environment", it needed a thorough consolidation of technology and expectation to reestablish new confidence.
Research efforts in the nineties then mainly focused on experiments with multi-channel control and the integration of distributed actors into so-called smart or intelligent structures. However, because of high actuator and control efforts, related engineering solutions are expected to be implemented in singular applications only.
A successful way for larger scale implementations of active technologies could be pointed out around the year 2000 by limiting related efforts to feasible applications in "simple cases". These promising applications are

- actively supported headsets and ear protectors
- active elastic mounts (vibration isolators)
- active sound attenuators in ducts and pipes and
- active control of interior sound in small volumes (e.g. cars)

While active ear protectors have become mass products, active isolators are available technology which, for operational application in practice, needs particular circumstances or requirements (including financial aspects), however. This is equally true for active duct- and pipe-attenuators where further limitations are caused by acoustic power and thermal constraints.
Altogether active methods are well understood today and this applies to both, the physical/acoustic and the control engineering part of the whole electro-acoustic system describing any active system. Both areas have been investigated systematically and described comprehensively ([14],[16]). As presently available signal processors allow real-time computations for highly complex algorithms even, current technological limitations are mainly due to actuators (loudspeakers) and their low-frequency constraints.

5.2 Active control of car interior sound

Today's most promising application area may be seen in active control of small volumes like the interior (passenger compartment) of cars. Starting from a demonstrator being able to compensate the second engine order and, at the same time, to generate additional controlled engine orders, this approach allowed to extend the scope from compensating existing components (Active Noise Control, ANC) to adding new components (Active Sound Design, ASD) of sound. This was the basis for further product oriented developments.

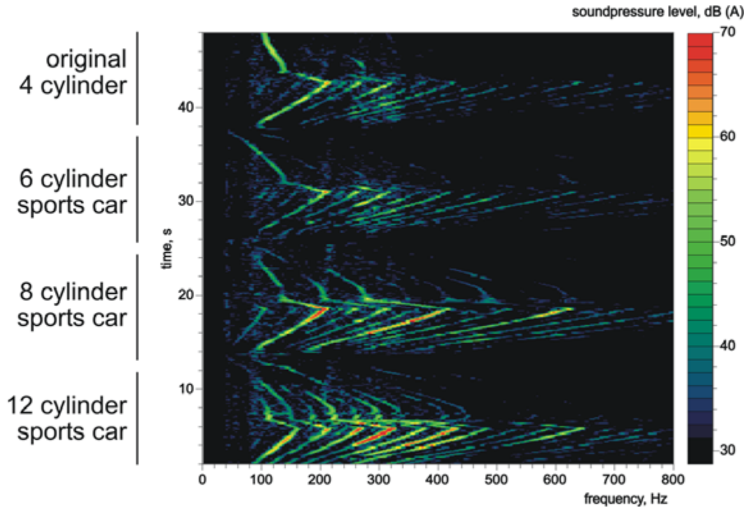

Figure 14 – Active control of car interior sound (active sound design, ASD)

Fig. 14 shows how the sound characteristics (i.e. the particular composition of engine orders) can be changed within the same car by just switching the operational modes of an ASD system. It should be noted that all engine sounds were perceived and assessed as highly authentic in all aspects: in its load dependence, its combustion characteristics and in the spatial localization. This authenticity together with the technical feasibility encouraged further development of the system as an individual tool to assist and support context true subjective assessments of engine sounds under real driving conditions. For test cars equipped with a set of typically four to six microphones and access to some CAN bus signals (rpm and load), a set of hard- and software equipment (later called m|klang®, [17]) was available to allow for real time modifications of the perceived engine sound while driving the car. The frequency range of operation was specified up to about 250-300 Hz, allowing extensions to higher frequencies for particular microphone positions. This tool was highly welcome and used by the automotive industry as a most valuable extension of stationary sound studios and simulators (providing "virtual reality") to driving test labs (providing "real virtuality", [17],[18]).
Starting from the success of this flexible ASD system development tool it was just consequent to take this system and technology as a basis for model customized solutions in OEM series applications. The motivation to go this step was manifold but has been dominated perhaps by the high flexibility in adapting car interior sounds to specific target requirements. However, although being very attractive since long, this option had to overcome some fundamental reservation against "synthetic", non-mechanical sounds within mechanical, engine driven environments before getting accepted in reality. But the authenticity of test implementations may have helped to pave the way for a breakthrough in series applications.
In this context special attention has been given to active control of car interior sound for engines with cylinder on demand technology. This technology is attractive to increase fuel efficiency by switching from 8 to 4 cylinder operation at specific operation conditions. The main task of such ANC systems then is to compensate for the characteristic 4-cylinder 2nd engine order. To illustrate this approach, an example of an Audi S-series solution (for the 4.0 TFSI engine with cylinder on demand technology) shall be described here. More details can be found in [19].
The respective ANC system utilizes 5 speakers which are part of the regular interior sound system and 4 microphones mounted into the headliner. The system is integrated into the "advanced sound" audio DSP amplifier and based on a SHARC floating point DSP. The amplifier is networked via MOST, an extra RPM pulse signal is added to reduce relevant latencies. Basic features include engine order based ANC for up to 8 relevant engine orders to be controlled in the whole passenger compartment. The ANC control frequency range is 32 to 250 Hz.

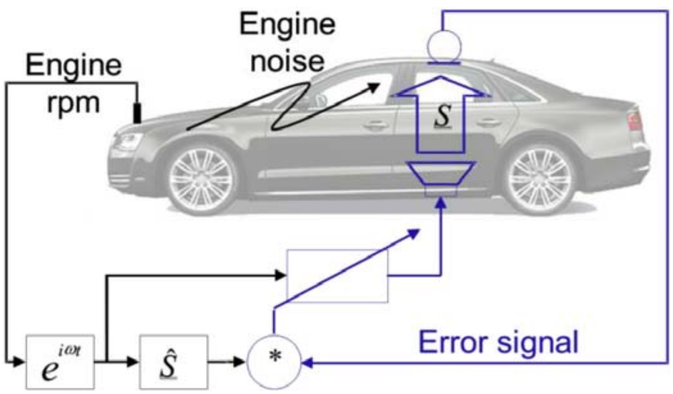

Figure 15 – Block diagram of in-vehicle ANC system. blue part: feedback control loop

Figure 15 shows the typical block diagram of a modern vehicle interior ANC system. It comprises an engine rpm pick-up with the engine rpm used to generate some harmonic signal of the appropriate engine order frequency. This signal is then fed through some adaptive signal processing in the filtered-x configuration already discussed, $\hat{S}$ denotes the acoustical transfer function estimate (model, typically based on a FIR-filter to be adapted to eventual changes in the transfer characteristics) used for filtered-x filtering while S denotes the physical transfer function (plant). So, from a traditional ANC perspective, we have (adaptive) feedforward control and setting up the adaptation in a stable way will guarantee good system performance ([19]).

To summarize this overall system performance, we use spectrogram plots of a full-load/wide open throttle run-up for both, 4 and 8-cylinder mode. This is not an easy measurement to be done especially at 4-cylinder mode because full load here means the maximum torque below the ECU 8-cylinder switching limit. Figures 16 and 17 ([19]) show the results for 4th gear inside an S8 vehicle. All of these measurements were taken on a roller dynamometer, so there is significant low order rolling noise captured during the measurements (below 1st engine order). However, this is not related to the ANC system and its performance.

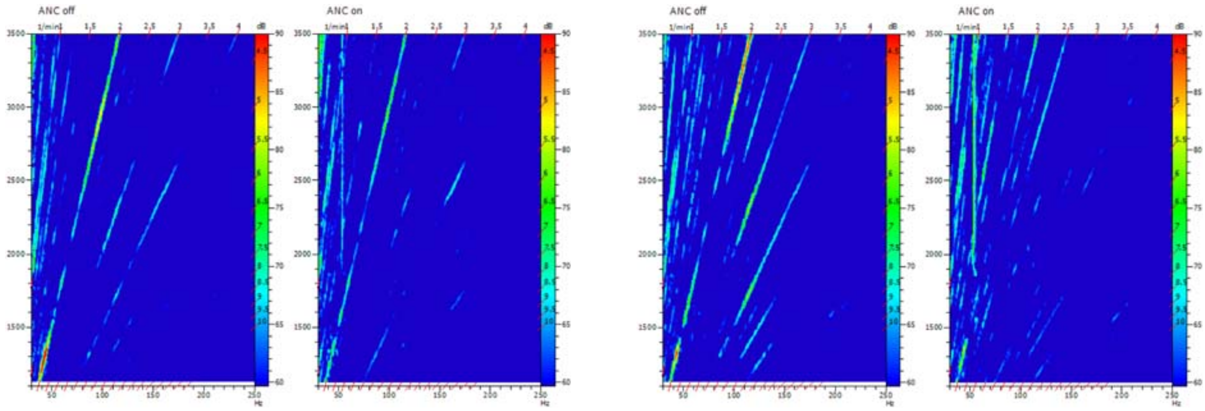

Figure 16 - S8 sound pressure for 4-cylinder operation, 4th gear at max torque,
at front left (left) and rear right (right) measurement position

As can be seen from figures 16 and 17, the ANC system is capable of reducing several (up to 8) engine orders at the same time for both, the front left and the rear right measurement positions. Also, by comparing corresponding 4- and 8-cylinder mode operations, it can be stated that the initial spectral differences between the related sounds are smoothed down to much more similarity, thus reducing the acoustical perception of the switching process.

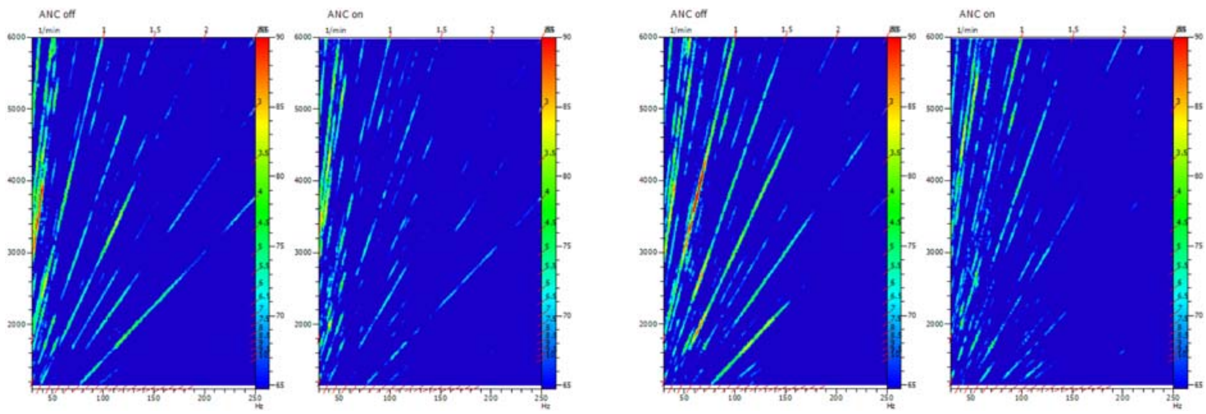

Figure 17 - S8 sound pressure for 8-cylinder operation, 4th gear at max torque,
at front left (left) and rear right (right) measurement position

5.3 Active control of sound and vibrations - summary

Unlike tyre/road noise modelling and gradual R&D progress in low noise road surface design, the way to state of the art technology in active sound control was characterized by many detours and wrong assessments. Nevertheless, despite considerable investment losses, research and development finally succeeded to

- clearly specify the physical and signal processing limits, to
- provide proven concepts and solutions for a future where existing technical limits will be overcome and to
- provide tools and solutions for marketable products and singular engineering solutions

A breakthrough in applied or applicable technology has been achieved so far in acoustically simple cases only, particularly for small volumes (headsets, car interior) and for compact sources (active mounts).

6 Conclusions

By increasing the acoustic quality of life, sound control engineering has essentially contributed to make life more worthwhile. This has made acoustics an indispensable interdisciplinary field. The resulting involvement obliges acoustics to promote its technical qualification as well as its further development in the interdisciplinary field of research, technology and application to be able to cope with future demands of comfort and environmental compatibility.

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