INCE: 76

CALCULATION OF NOISE CONTROL BY NUMERICAL METHODS - WHAT WE CAN DO AND WHAT WE CANNOT DO - YET

Fülöp Augusztinovicz
Technical University of Budapest
Department of Telecommunications
H-1111 Budapest, Sztoczek u. 2, Hungary

INTRODUCTION

Numerical methods have been used in acoustics for nearly three decades now, and the volume of literature as well as the number of academic, industrial and commercial codes and software packages is rapidly growing. The development of numerical techniques has largely been motivated by the highly competitive car industry where FE analysis has already been used as early as the late seventies [1], and numerical simulation as a design tool has become part of everyday routine in product development [2]. Similar driving force of the development was the highly technical requirements of the aerospace industry [3]. One can also witness a strong integration tendency in the software industry nowadays, resulting in a fully integrated design environment (mechanical computer aided engineering, MCAE) [4], [5].

Nevertheless, the application of numerical methods in acoustics is not yet completely widespread. Even though a wide palette of various methods is available [6], numerical techniques still face criticism from time to time for various reasons [7] and their use to predict noise reduction and to design optimum noise control still seems to be far from general practice in a number of industries. Except for some recent works, appearance of real industrial case studies in the public literature are sporadic (or at least reluctantly published), and validation of new numerical methods on large-scale industrial test cases is the exception rather than the rule.

The aim of this paper is to overview the present state-of-the-art, the strength and weakness of numerical techniques for calculating noise control - all these mainly from the practitioner’s point of view. An outlook to some possible future developments is also presented.

1. NUMERICAL PREDICTION AND SIMULATION METHODS

Generally speaking, the ultimate aim of all numerical methods is to describe the sound field in the considered system, based on the numerical solution of some form of a basic governing equation. Depending on the formulation and on the extent of simplification of this basic equation, the complexity of the problem as well as the necessary computational effort and the obtained results can vary extensively. Some methods (such as statistical energy analysis, SEA) require engineering judgment rather than serious computational power, and meaningful estimations can be obtained by very simple means. On the other extreme, pedigree numerical techniques such as the Finite Element (FE) and the Boundary Element (BE) methods, especially if they are used to solve coupled problems, set very high standards against computer hardware and performance. Accordingly, the obtained results can range from an approximate estimation of some overall statistical parameters up to a detailed description of the sound field in a localized region under rather general boundary condition such as mean fluid flow, temperature gradient, nonlinearities etc.

It is not the aim of this paper to review all these numerical techniques; instead, stress is focussed on the most familiar FE and the BE methods. Apart from some classical milestone works, emphasis is on reviewing the recent literature when selecting the references, herein. Even so, compilation of an exhaustive list is impossible and perhaps unneccessary, too.

1.1. Finite and boundary element methods

The Finite Element (FE) method. The application of the FE method to acoustical problems dates back to the mid-sixties when Gladwell and Zimmermann developed a common energy formulation of structural and acoustical theory for the solution of the Helmholtz differential equation (viz., the wave equation reduced to harmonic time dependence) [9]. Important early contributions were made by Craggs and others [10] to [12] by introducing damping and boundary flexibility in FEM. An important breakthrough was tackling coupled problems where a mutually interdependent structural and acoustical subsystem is solved simultaneously [12]. The method was used at an early stage for practical problems as well [13].

The Boundary Element (BE) method. Unlike the FE method, the Boundary Element (BE) method is used to solve the Kirchoff-Helmholtz integral equation. Since it is based on a surface integral representation of the problem, BEM reduces the dimensionality of the problem by 1 (a 2D mesh is sufficient instead of a full 3D mesh). It is generally felt that this is a major advantage and the method is thereby computationally more effective.

The basic, so-called direct BEM method was extended later to handle more complex problems. Thin structures can best be analyzed by the indirect approach whereby the primary variables are pressure differences and gradient differents [14]. New mathematical solution methods have been introduced [15], formulations dealing with multiple domain problems [16], general boundary conditions [17], transient problems [18] and random field excitation have been suggested [19].

A common and serious drawback of all BE methods has always been, and still is, the non-uniqueness of the numerical solution for frequencies which are identical or close to an eigenmode of the interior of the radiating/scattering object. Various schemes have been suggested to reduce the effect [20], [21].

Mixed (FEM/BEM) approaches. An unambiguous classification of a real-life problem into one of purely interior or purely exterior problems is often difficult, if not impossible. The modeling of a silencer in a ductwork, or a partial enclosure around a noisy machine necessitates dealing with the interior of the system and the outside environment. These problems can readily be handled by means of a mixed, FEM/BEM approach [22]. The mixed approach is also appropriate to take into account the interaction of structural and acoustical subsystems. Usually, the structural part is described by a structural FE model, the acoustic part by an acoustical BE model, and the problem is solved simultaneously as a coupled, interdependent whole.

1.2. Alternative approaches to traditional FEM and BEM

Traditionally, FEM is used to analyze interior problems such as identification of cavity resonances under given boundary conditions, while BEM is considered to be the most appropriate method to tackle radiation and scattering problems. With the evolvement of a number of alternative approaches extending the application area of both methods, these clear-cut divisions are now somewhat blurred.

The common idea of a number of recent FE extension methods is that the Sommerfeld radiation condition, viz., that sound waves should vanish toward infinity, can be satisfied in a FE scheme of affordable computational cost too, if so called infinite elements are introduced [23]. Wave envelope elements are a special variant of infinite elements which have been used for solving radiation problems with success [24], [25], [26].

An extremely promising infinite element method has been introduced recently which seems to be a serious challenger of the BEM, based on a prolate spheroidal multipole expansion. A good summary and comparison of these alternative approaches is given in [27].

Another important endeavor of ongoing research work is to extend the frequency limits of numerical methods toward higher frequencies, in order to narrow the medium frequency range or “twilight zone” where numerical methods are no longer, and statistical methods not yet, appropriate to solve problems successfully [8]. The merge of energy and FE methods has been attempted [28], and principles of fuzzy logic introduced [29]. More validation work and practical applications of these methods is required before final conclusions can be drawn, but the perspectives are promising.

As can be seen, numerous methods and approaches have so far been worked out, and one is tempted to presume that the available armory of numerical techniques is sufficient to tackle the great majority of practical problems with success. Still, the noise control engineer is very often confronted with the practical limits of otherwise well established techniques, and a number of major modeling problems are still open. The next section of the paper deals with these issues in more detail.

2. PROBLEMATIC ISSUES OF CALCULATION OF NOISE CONTROL

2.1. Accuracy

In order to predict the efficiency of a noise control measure, the designer has to compare two different situations: the effect of a design modification, or insertion of a noise control element such as a barrier, muffler or similar, compared to a reference case. The resulting acoustic quantity - usually sound pressure level in a well defined point or set of points - is calculated twice (before and after the modification, with and without the control element) in order to evaluate the effect of the noise control measure, while all other parameters are kept constant. According to basic rules of differential calculations, the relative error of the noise level reduction calculation is much higher than that of the two predictions. Should the case occur for example that the true effect of the noise control measure is a minor attenuation, even small prediction errors can easily result in slight amplification. This kind of error can sometimes be critical, especially in the case when the aim of the design is to meet a given legal requirement. On the other hand, the designer sometimes requires some qualitative information from the calculations only, in order to help to select the most appropriate design option or to make rough construction decisions. The exact value of the reduction may then be of minor importance.

2.2. Source modeling

One of the major stumbling blocks of meaningful noise control calculations is the issue of representative, still affordable source modeling. One can say that the feasibility of a whole calculation procedure can sometimes revolve around whether or not an adequate source description is available.

Very often the prediction is based on a **modal model** of the source. This is usually the case when the source does not yet exist, but a structural FE model and the forced response of the system is already known. Assuming that the structural FE model describes the source behavior in a proper way, meaningful sound field predictions can be performed. The accuracy of the calculations can be further improved if the calculated FE model is updated by some measured frequency response functions. Even if the number of measured degrees of freedom (DOFs) are considerably lower (mostly by orders of magnitude) than the calculated DOFs, the accuracy of the prediction can be improved considerably. An example of the good performance of this method is given in [30].

In case of complex, real-life sources the development of a modal model is not easy. Still, remarkable progress has been made recently in the development of a simulation tool aimed at predicting surface vibration of a gasoline engine [31]. The procedure consists of calculation of forced vibration of the engine, based on eigenmodes of the vibrating structures and calculation of excitation forces from engine operation parameters, extended to a number of operating mechanisms including nonlinear effects as well. The achieved accuracy of the calculation is noteworthy: deviations between 1 to 4 dB has been found. Nevertheless, the procedure is rather elaborate and considerable effort is needed to derive the necessary input data, therefore its generalization for various sources is not likely in the near future.

Instead, **surface vibration** of the source can directly be measured and used as prescribed velocity boundary condition in the course of a FE or BE calculation. The method is simple to conceive but sometimes difficult to realize by means of a traditional measurement setup in practice, mainly for simple practical reasons (too many measurement DOFs, hot surfaces, long-term stability of the source etc.). If the surface of the source is extended but not too complex in shape, the use of a scanning laser vibrometer can be a viable solution. If the source is too large with respect to the required spatial resolution however, the necessary measurement time rapidly becomes prohibitive.

Another, very promising source description method is offered by a new method of rapidly evolving laser technology. The extension of the laser speckle interferometry, referred to as **holographic or double pulse measuring technique** makes use of two laser “snapshots” at two closely spaced timing points, while the source is excited by a harmonic excitation force [32]. The interferograms are recorded by means of an off-the-shelf CCD camera at a large number of grid points simultaneously, from which the deformations are determined by appropriate image processing techniques. Unlike with normal laser speckle interferometry which results in a qualitative picture of the vibrations only, the obtained displacement can be properly scaled and the surface vibration distribution can be determined with extraordinary spatial resolution within a very short measurement time.

A much less demanding workabout of the source description problem is the method of **equivalent substitution sources** which attracts considerable attention nowadays [33] to [37]. The basic idea of the method is to substitute the original, complex source by a much smaller number of substitution elementary sources. The characteristics and source strength of these substituting sources can be based on various assumptions and principles such as equivalent volume velocity, equivalent power or other least means square estimation algorithms. One practical application of the method will be discussed below in paragraph 3.4.

2.3. Modeling of absorption and other material properties

Due to its practical importance for noise control calculations and also from the theoretical point of view, proper modeling of damping (in mechanical systems/subsystems) and absorption (in acoustical systems/subsystems) is another essential, though not easy problem.

Sound absorbing materials can be divided into two basic groups, based on their characteristics and operating mechanisms: locally reacting and bulk reacting materials. **Locally reacting materials** can be characterized by their normal acoustic impedance which can be calculated from basic mechanic parameters (flow resistivity) of the material, or derived directly from an impedance tube measurement. The application of locally reacting materials in numerical models is the most usual approach in standard BEM calculations, and can be applied for FE calculations as well. A drawback of this solution is that normal impedance as measured in the impedance tube is only representative for nearly normal incidence of sound waves.

Bulk reacting materials are characterized by the characteristic impedance and complex propagation constant. These parameters can be derived from measurements [38] and applied for any subset of elements of the FE model in most acoustic FE codes, enabling a more realistic, still rather straightforward modeling. In case of BEM, bulk reacting materials can however be modeled only if the software enables the analyst to define various fluid characteristics for different parts of the model (multi-domain BEM, [16], [17]).

It is not easy to decide, whether the simpler, locally reacting assumption is satisfactory for the given problem or bulk reacting description is to be drawn into the analysis [39]. Little information is available comparing the two approaches on the same problem [40], and designers would need some guidelines on the best practice to follow.

Eventually, a new dimension of acoustic modeling problems has arisen in relation to **composite materials** which offer high strength-to-weight ratios and provide good transmission loss characteristics, therefore they are used extensively in the automotive and aerospace industry. The vibroacoustic behavior of these materials are controlled by strong and complex fluid-structure phenomena. Various numerical procedures and programs have been developed to tackle the problem, including both pure FEM and BEM methods based on the Biot theory of porous materials [41], [42] as well as coupled FEM/BEM approaches [43]. The Biot theory provides good estimation accuracy and physical insight for a number of various test cases. A practical problem is however that the necessary input data (frame density, porosity, tortuosity and coupling coefficient) is not known for most materials, and their measurement requires special skill and equipment.

2.4. Production variance

A number of authors have called attention to the existence of production variance of vibro-acoustic characteristics of nominally identical serial products in different contexts recently [44] to [46]. Variations in amplitudes up to 10 dB and in modal frequencies up to 10 % and even higher were established. The inherent consequence of this variance is that conclusions, drawn from a numerical calculation referring to an item selected at random, will not be representative as a whole. Pessimistically formulated, this could mean that any non-statistical methods such as numerical ones are unable to provide conclusions relevant to prototype development, or at least their accuracy is limited.

2.5. Computational costs

Numerical techniques are notoriously computation intensive. The required computer storage sizes and computation times are progressively dependent on the relative spatial resolution of the model; or considering the limits the other way round, given the model size and acceptable solution time of the problem, the applicable maximum frequency of calculations is determined. As experience shows, smaller models can be analyzed by using the BE method within reasonable limits but even modern, powerful workstations are not yet fully appropriate to solve really large-scale industrial problems.

One should keep in mind however that with the development of computer technology, application limits are steadily pushed towards larger model sizes and higher frequencies. As a comparison of various benchmark tests reveals [74], computer speed is still steadily increasing every year. This means that, say, before the end of this century, BE calculations on a model such as discussed in paragraph 3.4 will require CPU time which is affordable under usual industrial circumstances too. Further developments worth mentioning is the ceaseless, and successful, search of software companies for new, more effective matrix solvers and the rapid advance of parallel processing. As a result, the application frequency range of numerical techniques is anticipated to double every 5 to 7 years - an appealing perspective both to developers and users of the technique.

As already mentioned in paragraph 1.2, another major improvement which can essentially reduce the computation costs of radiation problem solution is the introduction of a new kind of infinite element. Fig. 1 depicts the relative performance of the technique with respect to a traditional BE solution. As can be seen, the gain is more than two orders of magnitude for large model sizes, making otherwise difficult problems easily tractable. Note that researchers in BEM are also striving for new techniques, e.g., panel clustering and multipole expansions.

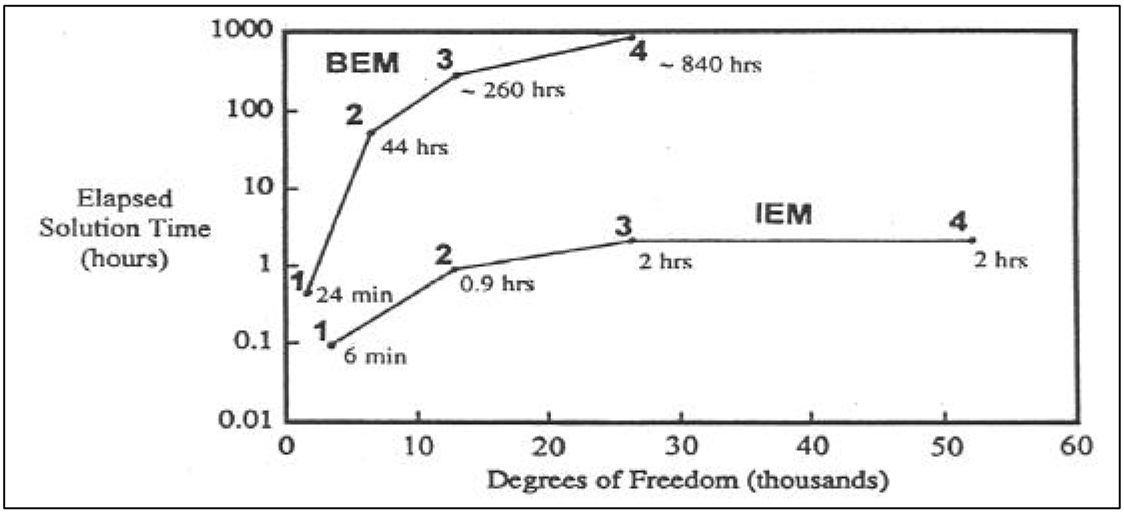

Fig. 1. Comparison of computation time of the BE and IE method (after Burtlett, [27])

3. PRACTICAL APPLICATIONS OF NUMERICAL METHODS FOR THE CALCULATION OF NOISE CONTROL

In order to demonstrate the potentials and difficulties of some up-to-date numerical techniques for the qualitative or quantitative determination of noise control, some few practical examples are reviewed below. The limited space allows only discussion of the most typical ones; further applications can be found in the reference list.

3.1. Prediction of design versions: application for engine noise radiation

One of the main application area of numerical noise control prediction techniques is the decision in the early product development phase, which design version out of possible options is the most appropriate from the noise control point of view. The issue can be approached by just repeating some straightforward calculations on different parts [47] or subsystems [48] of the investigated product. By introducing the concept of sensitivity analysis [49] product development can be performed in a more systematic way [50], [51]. Targeted optimization software tools are also in development [3] and even commercialized [52].

Due to the primary practical importance of optimal engine design, calculation of engine noise radiation has always been in the focus of numerical noise predictions. Early predictions have only dealt with the engine block itself [54], based on a simple modal model and usually the BEM approach. The accuracy of these calculations, especially if the modal expansion method is also implemented, is very good and enables the designer to evaluate the effect of design changes with reasonable confidence, assuming that the excitation is simple and described in a representative way by simple methods.

In order to bring the application area of the predictions closer to reality, considerable research effort has recently been put into the development of a more realistic engine noise prediction scheme [55]. While the response of the engine was described by a carefully updated modal model, various source mechanisms of the fired engine are simulated. In order to improve the accuracy of the method, frequency response functions were also determined experimentally on a similar engine type. As a result, surface vibrations could be determined in two different ways, and the radiated noise calculated. Using these procedures, two design versions of a gasoline engine, one with open and one with closed deck were compared. The obtained results were qualitatively indicative, though the agreement between the fully computational and the mixed approach was not satisfactory. As discussed earlier, more recent methods [56], [31] aimed at improving the source description of real-life engines have resulted in further improvement of accuracy.

3.2. Calculation of muffler and silencer performance

The prediction of acoustic performance of ducts, silencers and mufflers seems to be a well established area of noise control. Depending on the design, application and operating conditions, a number of physical models have been developed, different computational schemes are in use. Comprehensive textbooks do exist [57], and the topic was also reviewed in an exhaustive Inter-Noise review paper some time ago [58]. Nevertheless, due to the practical importance of the problem as well as some new developments, it is worth mentioning the issue of automotive mufflers here.

Newer generation engines are designed to lower fuel consumption and to optimize engine power and torque characteristics, resulting in steadily higher requirements against automotive exhaust systems. Leading exhaust manufacturers have already long substituted the familiar ‘trial and error’ approach for systematic design methods based on various physical models. The most widely used approach is the transfer matrix method which is based on the assumption of low sound pressure amplitudes (thus of full linearity) and one-dimensional sound propagation (limiting the useful frequency range). The acoustic model can be extended by fluid dynamics parameters such as mean fluid flow, temperature gradient and visco-thermal damping, but the linear assumption cannot be overcome. By comparing the method with results of a non-linear, similarly one-dimensional CFD calculation, it has been shown that this shortcoming can become decisive even at relatively low pressure amplitudes [61]. Another option is to use a hybrid approach, consisting of linear transmission loss prediction method combined with non-linear source description [60].

Results of predictions begin to deviate from measured data towards higher frequencies where cross modes are getting more relevant, no matter whether linear acoustic or non-linear CFD calculations are concerned. Numerical techniques have their clear advantages over more simple methods to investigate muffler performance just in this frequency range. As a simple example, it is shown in [62] that a simple offset of the inlet tube with respect to the outlet tube considerably changes the transmission loss of the system, which in turn can be predicted by using BEM with good accuracy. Another advantage of the numerical, mainly BEM calculations is the capability of good graphical visualization of the sound field inside the muffler, in order to get a better insight into physical phenomena for important frequencies [7], [65].

Even if performance of an exhaust muffler is optimized in terms of air-borne sound transmission loss, designers often face problems arriving from excessive shell noise [63]. The reasons of shell noise problems are obvious, and rather complex fluid-structure interaction phenomena where FE and BE modeling is an unquestionably appealing approach. However, the appearance of shock waves, temperature gradient, proper description of the inherently non-linear source and other effects can equally play an important role. All these problems make proper modeling and optimization of an automotive intake or exhaust silencer a task which is still far from being solved with currently available methods [64].

3.3. Sound barriers

The design of sound barriers is another field where well established computational methods and even design guidelines and standards are at the designers’ disposal. A renewed interest in numerical alternatives to those analytical methods is however to observe, which lands itself to be explained by the need to analyze more sophisticated shapes, new acoustic constructions and materials.

Most of the numerical calculations make use of a two-dimensional BE method [66] to [68], where sources are modeled as point sources and acoustic absorption of construction works and level ground is modeled by normal acoustic admittance. (This is not really correct in case of porous asphalt, therefore other solutions were also used [67]). In spite of the simple model, good agreement is found.

The accuracy of the usual, analytical barrier design methods can be questioned especially when the barrier is of finite length. Considering the uncertainty of correction factors in case of complex barrier/road environment geometries and also the high costs involved in road noise barriers, the use of a detailed, 3D BE analysis such as in [69] can be a viable solution. Even in case of a high-performance workstation, the size of the problem to be analyzed can easily become prohibitive, therefore some simplification has to be made [70]. Once again, we face a situation where not the principal but just practical problems, viz., computational power, are the limiting factors.

3.4. Close-fitting partial enclosures

The design of partial enclosures such as those fitted onto noisy machines, quiet trucks etc. poses a difficult problem, where engineering judgment and experimenting are still the preferred tools to extended calculations. There are quite a few acoustic phenomena which can significantly influence the noise reduction of this kind of elements. These include, among others, sound radiation from the source, interactions within and sound propagation along the gap between the source surface and enclosure, transmission through thin plate-like structures, sound absorption in the absorbent lining, diffraction through openings etc. It is understandable that such complex, mutually interacting systems are not amenable to any single calculation technique for predicting the performance in the whole frequency range of interest.

In order to evaluate the strengths and weaknesses of various techniques, a number of prediction methods have been investigated in the context of a more extended investigation, aimed at developing design and measurement methods for quiet heavy vehicles [71]. Even though not without limitations, the most suitable technique was found to be an indirect BE approach, combined with a source substitution procedure. (One has to note at this point that a similar comparative study might come to a different conclusion if it was performed today. This is because of considerable improvements of some FE techniques and the mixed, FE/BE approach, as discussed in paragraph 1.2. above.)

The calculation started from a surface mesh of the engine, assumed to be entirely rigid. The radiation of the engine was represented by 100 or so hypothetical monopoles which are presumed to be on the rigid engine surface, radiating the same amount of energy which is measured by intensimetry under real operating conditions. The radiated sound pressure levels are calculated for appropriately selected points 7.5 m apart from the truck, once without the enclosure and once with the enclosure in place. The calculations were repeated for a number

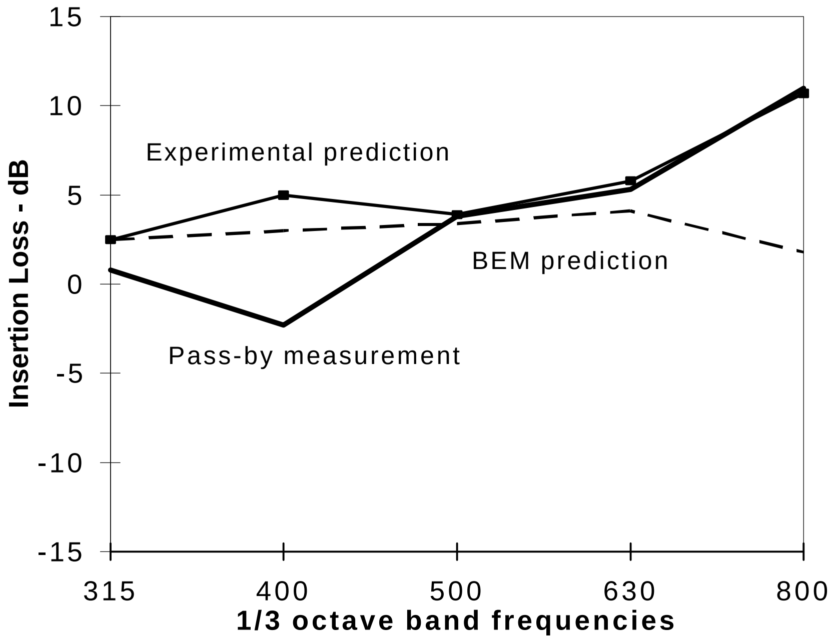

Fig. 2. Comparison of measured and predicted insertion loss of a close-fitting engine enclosure of a heavy diesel truck [73]

of single frequencies and then summed to obtain third-octave band insertion loss (IL) spectra.

Even though the calculated radiated field was not very accurate in absolute sense, the accuracy of the obtained, relative insertion loss spectrum is reasonably good as compared to validation measurements and other calculations, based on pure experimental techniques, see Fig. 2. The deviations at lower frequencies can be explained by different operating and modeling conditions as well as the appearance of non-uniqueness problems (especially in the enclosed calculations); in the 800 Hz band the effect of inappropriate spatial resolution can be observed. It is felt and could be shown for smaller and simpler models that the presence of the close fitting enclosure has significantly worsened the numerical conditioning of the problem [72]. While those precautions taken to avoid irregular frequencies were sufficient for the freely radiating case, this was not the case with the enclosure in place. The radiated sound was overestimated for some frequencies, resulting in seemingly lower, sometimes even negative insertion loss value for the enclosure.

Since the model size of the problem was rather big, the computational costs were substantial too. A full run, consisting of two sets of calculations for 30 frequencies required almost 14 days pure CPU time. Taking into account the necessary time to prepare the meshes, command files, postprocessing steps and all the necessary file manipulations, to obtain the single curve of Fig. 2. took certainly more time than one man-month. This time frame is mostly unacceptable in a real industrial environment.

4. CONCLUSIONS

In the preceding review we have outlined some recent developments in numerical prediction methods, with special emphasis on calculating noise control. A critical evaluation shows that while a great number of various techniques exist to tackle various problems, it is not easy to select the really appropriate approach. Moreover it is difficult to master to obtain good quantitative noise control results without a deep and thorough understanding of all aspects of numerical acoustic modeling.

Numerical techniques have proven beyond dispute their capabilities to predict sound fields - and therefore sound field differences brought about by noise control measures as well - with reasonable accuracy, provided that *all boundary conditions are taken into account properly* in the model. The real art of numerical modeling is nowadays, *how and to what extent a real object may be simplified for modeling purposes without losing much in accuracy but still retaining reasonable computational costs*. A closely related issue is how to determine the useful frequency range of a numerical simulation, or vica versa, how to select the modeling parameters in order to ensure the required frequency range. (According to experience, the usual $\lambda/6$ rule is not more than a rough rule of thumb for practical problems.) The end users of the technology need as detailed guidelines as possible from method developers in this aspect.

Insufficient experience seems to be on how well-established numerical techniques behave when applied to large-scale industrial problems. Some experiences suggest that numerical conditioning of the problem is worsening with increasing problem size; other researchers report on good prediction accuracy even for very large structures. The importance of exchange of information and of experimental validation can hardly be overestimated in this context.

The more wide-spread use of numerical techniques in noise control design and development still seems to be impeded by the high requirements of the technology, both in terms or computational power and operator skills. This means that even though a great many problems such as nonlinearity, fluid flow effects etc. needs to be included in future developments of the technique, there is still a lot to be done to bridge the gap between already existing methods and their potential users too.

Even if the problem cannot be modeled properly, numerical techniques can provide invaluable help in better understanding physical phenomena, radiation, propagation and absorption mechanisms in noise control systems. Maybe the obtained results are not exact in quantitative terms, still general tendencies can be appropriately interpreted. In the author's understanding, *the real merits* of state-of-the-art numerical techniques *lie just in their capability to predict tendencies* for complex systems which were untractable otherwise, rather than being able to tell noise reduction values within 1 dB accuracy. For this reason and also for the ease and speed of simulations of a great variety of physical systems, numerical techniques are very useful tools in acoustic and noise control education.

5. OUTLOOK FOR THE FUTURE - CONCLUDING REMARKS

Cellular Neural Networks. In spite of the breathtaking development of digital computer technology, the most stringent factor limiting the use of numerical techniques more extensively is still nothing else but computing power. Maybe the solution to dissolve this bottleneck will arrive from a rather unexpected direction, namely, neural networks technology.

It can be shown that many complex computational problems can be reformulated as well-defined tasks where the signal values are placed on a regular geometric 2D or 3D grid, and the direct interactions between signal values are limited within a finite local neighborhood [75]. An invention, called cellular neural network (CNN) is an analog dynamic processor array which reflects just this property: the array consists of analog processing elements which interact directly within a finite radius [76]. A CNN differs both from cellular automaton arrays since the cells handle continuous, not binary signals, and also from general neural networks in so far as they capture the geometric, nonlinear, and/or delay-type properties in the interaction weights.

Due to their local connectivity, CNNs can be easily realized as VLSI chips and can operate at a very high speed and complexity. (A practical implementation, combining analog array processing with logic operations by incorporating distributed analog memory and programmability is suggested in [77].) At the same time, their potential application area ranges from object identification and image processing to the numerical solution of partial differential equations [78]. This is why phenomenal progress on CNN has been made from the first publication of the idea. Even though it is premature to guess the practical consequences of this new development for numerical acoustics before the first really large arrays will be put into operation, the prospect of CNN technology is certainly very bright.

"Fluid acoustics" - a new discipline? In the last decade or so, intensive cooperation and useful exchange of views and methods may be observed between structural dynamics and acoustics, giving rise to a new field called *vibro-acoustics*. Another major impact may be anticipated from the forthcoming merge of *fluid dynamics* and *numerical acoustics*. From the famous publication of Lighthill over the "acoustic analogy" [79] it is well known that non-linear velocity fluctuations in a turbulent flow may be considered as quadrupolar sources of noise. Advances in numerical methods now make possible the full simulation of turbulent flows. Navier-Stokes equations can be solved by numerical methods (direct numerical simulation, DNS) which are rather similar to those used in numerical vibro-acoustics. Some attempts have already been made to merge CFD methods with BEM [80] and also with FEM [81] . We have good reason to anticipate a major improvement in our understanding and efficient use of noise control technology from the cross-fertilizing effects of these areas.

6. REFERENCES

General papers

[1] D.J.Nefske, J.A. Wolf and L.J.Howell, “Structural-acoustic finite element analysis of the automotive passenger compartment: a review of current practice”. *J. Sound Vib*,

[2] U. Sorgatz, “Integration der numerischen Simulation in die Produktentwicklung”. *CIM Management*, Vol. 11. No. 4. 26-31.p. (1995)

[3] An exhaustive, early summary can be found e.g. in: E.H.Dowell, “Master plan for prediction of vehicle interior noise.” *AIAA Journal*, Vol. 18. No.4. 353-366.p. (1980).

[4] J. Leuridan, “Modal analysis - a perspective on integration”. *Proc. 10th Int. Modal Analysis Conf.,* San Diego, Vol. I. xxxiv-xxxx. p. (1992)

[5] J.-L. Migeot et al., “High performance computational environment for vibro-acoustic optimization”. *Proc. 21st Int. Seminar on Modal Analysis*, Leuven, Vol. III. 1641-1645.p. (1996)

[6] J.P. Coyette, H. Wynendaele and L. Cremers, “An overview of available numerical methods for automative acoustic design optimisation*”.* *NVH Solution Symposium ‘95,* 129-143.p. (1995)

[7] A.F. Seybert, “ The BEM in acoustics - physical insights and practical examples”. Proc. *2nd SYSNOISE Users Meeting,* Leuven, Part III.1. (1995)

[8] J. Leuridan, “Software for acoustics ... Crossing the chasm”. *Proc. Euronoise ‘95*, Lyon, Vol. 1. 17-32. p. (1995)

FE methods

[9] G.M.L. Gladwell and G. Zimmermann, “On energy and complementary energy formulations of acoustic and structural vibration problems”. *J. Sound Vib*, Vol. 3. 233-241.p. (1966)

[10] A. Craggs, “An acoustic finite element approach for studying boundary flexibility and sound transmission between irregular enclosures”. *J. Sound Vib.,* Vol. 30. No.3. 343-357.p. (1973)

[11] A. Craggs, “A finite element method for damped acoustic systems: An application to evaluate the performance of reactive mufflers”. *J. Sound Vib*., Vol. 48. No. 3. 377-392.p. (1976)

[12] O.C. Zienkewicz and P. Bettess, “Fluid-structure dynamic interaction and wave forces. An introduction to numerical treatment.” *Int. J. Numerical Methods in Engrg.,* Vol. 13. 1-16.p. (1978)

[13] R. LeSalver and G. Jennequin, “Méthode de de calcul pour les bruits basse fréquence dans un habitacle de voiture”. *Proc. 14th FISITA Cong.,* London, 90-100.p. (1972)

BE methods

[14] P.J.T. Filippi, “Layer potential and acoustic diffraction”. *J. Sound Vib.,* Vol. 54. No. 4. 473-500.p. (1977)

[15] M.A. Hamdi, “Une formulation variationelle par équations intégrales pour la résolution de l’équation de Helmholtz avec des conditions aux limites mixtes”. *Compt. Rend. Acad. Sci.,* Paris, Vol. 292(II), 17-20.p. (1981)

[16] C.Y.R.Cheng, A.F.Seybert and T.W.Wu, “A multi-domain boundary element solution for silencer and muffler performance prediction”. *J. Sound Vib.,* Vol. 151. 119-129.p. (1991)

[17] J.P. Coyette, C. Lecomte and H. Wynendaele, "A generalized boundary element model for handling complex acoustic problems*". NVH Solution Symposium '95*, 147-154.p. (1995)
[18] J.-P. Coyette, "Application of Finite Element and Boundary Element models to transient acoustic problems". *IX. Int. Conf. Vehicle Structural Mechanics and CAE*, Michigan, April 4-6 (1995)
[19] J.-P. Coyette and C. Lecomte, "A coupled FEM/BEM model for handling the vibro-acoustic response of structures subjected to random excitations*". Proc. Inter-Noise 96*, 2979-2984.p. (1996)
[20] A.J. Burton and G.F. Miller, "The application of integral equations to the numerical solution of some exterior boundary value problem". *Proc. Royal Society,* London, A 323, 201-210.p. (1971)
[21] A.F. Seybert and T.K. Rengarajan, "The use of CHIEF to obtain unique solutions for acoustic radiation using boundary integral equations."*J. Acoust. Soc. Amer.,* Vol. 81. 1299-1306.p. (1987)
[22] O.C. Zienkiewicz, D.W.Kelly and P. Bettess, "The coupling of the finite element method and boundary solution procedures". *Int. J. Numerical Methods in Engrg.,* Vol. 11. 355-375.p. (1977)

Special FE methods
[23] P. Bettess, "Infinite elements". *Int. J. Numerical Methods in Engrg.*, Vol. 11. 53-64.p. (1977)
[24] R.J.Astley and J.-P. Coyette, "Mapped wave envelope elements of infinite extent: Application to acousto-structural scattering". *Int. Conf. Recent Advances Struct. Dyn.,* Additional Papers Volume, Southampton, 1-10. p. (1991)
[25] L. Cremers and K.R.Fyfe, "On the use opf variable order infinite wave envelope elements for acoustic radiation and scattering". *J. Acoust. Soc. Amer*., Vol. 97. No. 4. 2028-2040. p. (1995)
[26] H. Allik and R.C. Haberman, "Calculation of radiation efficiency of complex structures using finite and infinite elements". *Proc. Inter-Noise 96,* 2963-2966.p. (1996)
[27] D.S.Burnett, "A three-dimensional acoustic infinite element based on a prolate spheroidal multipole expansion". *J. Acoust. Soc. Amer*., Vol. 96. No.5. Pt.1. 2798-2816.p. (1994)
[28] R.J. Unglenieks and R.J. Bernhard, "Prediction and verification of energy flow in a structure using an energy finite element approach". *Proc. 1995 Noise Vib. Conf. (SAE),* Paper #951305, Vol. I. 593-600.p. (1995)
[29] R.C. Haberman and H. Allik, "Application of infinite fluid elements and fuzzy structures to acoustic radiation from a cylindrical shell in water with internal structure". *Proc. Inter-Noise 96*, 2971-2974.p. (1996)

Source modelling
[30] U. Viersbach, R. Maurell, P. Guisset and J.-P. Rossion, "Engine noise radiation - Prediction and test comparison". *Proc. 1995 Noise Vib. Conf. (SAE),* Paper # 961342, Vol. II. (1995).
[31] B. Loibnegger and G.Ph. Rainer, "Design supporting analysis for powertrain noise and vibration". *Proc. Inter-Noise 96*, 3043-3046.p. (1996)
[32] R. Freymann, W. Honsberg, F. Winter and H. Steinbichler, "Holographic modal analysis". *Laser in Research and Engineering* (Ed. W. Waidelich), Springer Verlag Berlin, 530-542.p. (1996)
[33] Verheij, A.N.J. Hoeberichts and D.J. Thompson, "Acoustical source strength characterization for heavy road vehicle engines in connection with pass-by noise." *Proc. 3rd Int. Congress on Air- and Structure-Borne Sound and Vibration* (Ed. M.J. Crocker), June 13-15 1994, Montreal, Vol. I. 647-654. p. (1994)
[34] M. Ochmann, "Th source simulation technique for acoustic radiation problems". *Acustica*, Vol. 81. 512-527.p. (1995)
[35] F. Holste, "An equivalent source method for calculation of the sound radiated from aircraft engines". *Proc. 1st CEAS/AIAA (16th AIAA) Aeroacoustics Conf.,* Vol. II. 729-738.p. (1995)

[36] F. Augusztinovicz, F. Penne and P. Sas: “Calculation of sound radiation from sources, characterized by the equivalent power volume velocity method.” *Proc. 2nd SYSNOISE Users Meeting*, Leuven, Paper II.5. (1995)
[37] S.H. Yoon and P.A. Nelson, “Least squares techniques for the estimation of acoustic source strength spectra”. *Proc. Inter-Noise 96*, 3021-3026.p. (1996)

Modelling of porous and composite materials
[38] Ch. D. Smith and T.L. Parrott, “Comparison of three methods for measuring acoustic properties of bulk materials”. *J. Acoust. Soc. Amer*., Vol. 74. No. 5. 1577-1582.p. (1983)
[39] T. Zandbergen, “Do locally reacting acoustic liners always behave as they should?” *AIAA Journal,* Vol. 18. 396-397.p. (1980)
[40] R.J. Astley, “ “, *J. Sound Vib.* Vol. 117. 117- p. (1987)
[41] M.A.Biot, “Theory of propagation of elastic waves in a fluid-saturated porous solid - Part I., Part II”. *J. Acoust. Soc. Amer.,* Vol. 28. No. 168-191. (1956)
[42] J.P. Coyette, “Finite Element and Boundary Element models for predicting the vibro-acoustic behaviour of multi-layered structures”. *Proc. 1995 Noise Vib. Conf. (SAE),* Paper #951341, Vol. II. (1995)
[43] C.S.Pates, Ch. Mei and U. Shirahatti, “Coupled Boundary and Finite Element Method for analysis of composite structure-acoustic interaction problems”. *Proc. 1995 Noise Vib. Conf. (SAE),* Paper #951343, Vol. II. (1995)

Production variance
[44] M.S. Kompella and R.J. Bernhard, “Measurement of statistical variation of structural-acoustic characteristics of automotive vehicles”. *Proc. 1993 Noise Vib. Conf. (SAE),* Paper #931272 (1993)
[45] F.J.Fahy, “Statistical energy analysis: a critical overview*. Phil. Trans. R. Soc. London, A*, Vol. 346, 431-447.p. (1994)
[46] J. Plunt, “Generic limitations of vibro-acoustic prediction methods for product noise”. *Proc. Inter-Noise 96,* Vol. 3047-3052.p. (1996)

Application examples: design versions
[47] M. Hazel, C. Norrey, H. Kikuchi and -D. Tres, “Using predictive acoustic analysis to evaluate noise issues in under hood applications”. *SAE Conf. New Applications of Plastic Components in Vehicle Design (SP-1166),* Paper #960145 (1996)
[48] S.H.Jee, C. Birkett and B. Tsoi, “Passenger car interior noise reduction”. *Proc. Noise-Con 96,* 223-228.p. (1996)
[49] D.C.Smith and R.J.Bernhard, “Computing acoustic design sensitivity information using boundary element methods”. *Proc. 11th Int. Conf. Bound. Elem. Methd. Eng.,* Cambridge, Vol. 2. 369-383.p. (1989)
[50] R. Garcea, B. Leigh and R.L.M. Wong, “Development and validation of a numerical acoustic analysis program for aircraft interior noise prediction”. *Proc. Inter-Noise 92*, 935-938.p.
[51] S.P.Engelstad, K.A. Cunefare, S.Crane and E.A.Powell, “Optimization strategies for minimum interior noise and weight using FEM/BEM”. *Proc. Inter-Noise 95*, 1205-1208.p. (1995)
[52] J.-P. Coyette, P. Guisset and O. von Estorff, “The use of MSC/NASTRAN and SYSNOISE for evaluating global acoustic sensitivities of a vibrating structure.” *MSC/NASTRAN European Users Conference,* Vienna (1993)
[53] V.K. Zhang *et al:* ”Vehicle noise and weight reduction using panel acoustic contribution analysis”. *Proc. 1995 Conf. Noise Vib. (SAE),* Paper #951338. (1995)
[54] S.M. Kirkup, D.J. Henwood and R.J. Tyrrell, “Engine noise - practicalities and prediction. Part 3: noise prediction using the boundary element method”. *Proc. IME Int. Conf. Advances in the Control and Refinement of Vehicle Noise*, March 1988, Birmingham, Paper C33/88
[55] G. Busch, R. Maurell, J.Meyer and C. Vorwerk, “Investigations on influence of engine block design features on noise and vibration”. *Proc. 1991 Noise Vib. Conf. (SAE),* Paper #911071 (1991)

[56] P. Herster, E. Gschweitl and G.Ph.Rainer, "Use of airborne noise calculation to develop low noise engines". *Proc. 5th Int. Conf. Structure Dynamics: Recent Advances,* Southampton, 11033-1044.p. (1994)

Application examples: ducts and mufflers

[57] M.L.Munjal, *Acoustics of ducts and mufflers*. Wiley-Interscience, New York, 1987.
[58] A. Cummins, "Prediction methods for the performance of flow duct silencers". *Proc. Inter-Noise 90*, Gothenburg, Vol. I. 17-38.p. (1990)
[59] R.J.Astley and A. Cummins, "A finite element scheme for attenuation in ducts lned with porous material: comparison with experiment". *J. Sound Vib.,* Vol. 116. No.2. 239-263.p. (1987)
[60] P. Garcia, X. Mouton and F. Kunz, "Berechnung des Mündungsgeräusches einer Abgasanlage". *VDI Berichte Nr. 1007*, 505-522.p. (1992)
[61] Th. Morel, J. Morel and D.A. Blaser, "Fluid dynamic and acoustic modeling of concentric-tube resonators/silencers". *Proc. 1991 Noise and Vib. Conf. (SAE),* Paper #910072, Vol. I. 1-17.p.
[62] Ch-N. Wang, Ch-Ch.Tse and Y-N. Chen, "Analysis of three dimensional muffler with boundary element method". *Applied Acoustics*, Vol. x 91-106.p. (1993)
[63] P. Garcia, T. Jonas and C. Kuntz, "Shell noise from car exhaust systems." *Proc. FISITA '94 Congress* (1994)
[64] W. Eversman and J.A. Whire, "Acoustic modeling and optimization of induction system components". *Proc. 1995 Noise and Vib. Conf. (SAE),* Paper #951261. 207-215.p. (1995)
[65] A. Selamet and P.M. Radavich, "Helmholtz resonator: A multidimensional analytical, computational, and experimental study". *Proc. 1995 Noise and Vib. Conf. (SAE)*, Paper # 951263. Proc. 227-239.p. (1995)

Application examples: noise control barriers

[66] D.C.Hothersall, S.N. Chandler-Wilde and N.M. Hajmirzae, "Efficiency of single noise barriers". *J. Sound Vib.,* Vol. 146. No.2. 303-322.p. (1991)
[67] F. Anfosso-Lédée and M. Bérengier, "The prediction of combined effect of road noise barrier and porous road surface by BEM". *Proc. Inter-Noise 96,* 751-756.p. (1996)
[68] P.A.Morgan, C.R.Ross and S.N. Chandler-Wilde, An efficient boundary element method for noise propagation from cuttings". *Proc. Inter-Noise 96*, 3011-3016.p. (1996)
[69] J.C.S. Lai, "Application of the boundary element method to assessment of road traffic barriers". *Proc. 2nd SYSNOISE Users Meeting*, Leuven, Paper IV.2 (1995)
[70] A. Tekatlian and E. Premat, "Computer cost of a 3-D numerical model for noise barriers insertion loss." *Proc. Inter-Noise 96*, 3075-3080.p. (1996)

Application examples: close-fitting enclosures

[71] BRITE-EURAM Project No. 5414: "New pass-by noise optimization methods for quiet and economic heavy road vehicles (PIANO)"
[72] F. Augusztinovicz, P. Sas and F. Penne: "Comparison and verification of experimental and numerical models for the prediction of the efficiency of engine noise shields". *Proc. 1995 Noise Vib. Conf. P-291 (SAE),* Paper #951339, Vol. 2. 859-866.p. (1995)
[73] F.Augusztinovicz, P. Sas, L. Cremers, R. Liebregts, M. Mantovani and C. Bertolini, "Prediction of insertion loss of engine enclosures by indirect BEM calculations, combined with a substitution monopole source description technique". *Proc. 21st Int. Seminar on Modal Analysis* , Leuven, Vol. I. 55-68.p. (1996)

Related technologies

[74] Website of the Performance Database Server: *http://performance.netlib.org/performance/html/PDSbrowse.html*
[75] L.O.Chua and T. Roska, "The CNN Paradigm". *IEEE Trans. Circuits Syst.,* Vol. 40. No.3. 147-156.p. (1993)

[76] L.O.Chua and L. Yang, “Cellular neural networks: Theory & Applications”. *IEEE Trans. Circuits Syst.,* Vol. 35. 1257-1290.p. (1988). See also U.S. Patent 5140670, issued on August 18, 1992.
[77] T. Roska and L.O.Chua, The CNN universal machine: an analogic array computer”. *IEEE Trans. Circuits & Systems-II,* Vol. 40. 163-173.p. (1993)
[78] T. Roska, T. Kozek, D.Wolf and L.O.Chua, “Solving partial differential equations by CNN”. *Computer and Automation Inst. Rep. # DNS-4-1993*, Budapest (1993)
[79] M.J. Lighthill, “On sound generated aerodynamically”. *Proc. Roy. Soc.,* London, A, Vol. 211. 564-587.p. (1952)
[80] R.J.Epstein and D.B.Bliss, “An aeroacoustic boundary element method using analytical/numerical matching*”. Proc. 1st CEAS/AIAA (16th AIAA) Aeroacoustics Conf.,* Munich, Vol. I. 491-500.p. (1995)
[81] C.-H. Hsu, P.L.Spence and F.Farassat, “Ducted fan noise prediction based on a hybrid aerodynamic-aeroacoustic technique*”. Proc. 1st CEAS/AIAA (16th AIAA) Aeroacoustics Conf.,* Munich, Vol. I. 555-564.p. (1995)