

Analysis of Acoustic Absorption with Extended Liner Reaction and Grazing Flow

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Abstract

Acoustic absorbing liners are efficient and commonly used measures to reduce sound levels in many fields of application. The sound reducing performance of the liners is dependent on the acoustic state, defined by e.g. the flow and sound field interacting with the liner. To enable liner optimization the impact of these factors on the liner performance must be predictable. Studies of the impact of these factors were performed with existing experimental, analytical and numerical methods at low Mach number flows and material used in truck engine compartments. The study showed significant impact of both flow and sound field on the liner performance. The size of the impact of the flow depends on which of the existing methods and models that was used, implying the need of complementary methods. A new numerical method to model the boundary layer effect was for this reason developed in this work. The method was shown to predict the impact of flow correctly compared to the Pridmore-Brown solution and the method was computationally efficient. The sound reducing performance of a liner exposed to complex sound field and grazing flow can be predicted using existing methods together with the new proposed method. Extra care has to be taken when bulk reacting liners are considered since additional complications compared to locally reacting surfaces occur in presence the of grazing flow.

Keywords: Sound absorption, acoustic lining, non-locally reacting, boundary layer, grazing flow, sound field, transfer matrix method

Sammanfattning

Ett vanligt och effektivt sätt att reducera buller i många applicationer är att använda porösa ljudabsorbenter. Absorbenternas ljudreducerande prestanda är beroende av omgivande faktorer så som ljud- och strömningsfältet över absorbenten. För att möjliggöra optimering av absorbentens prestanda behöver inverkan av dessa omgivningsfaktorer kunna bestämmas numeriskt eller analytiskt. Faktorernas inverkan på ljudreduktionen har studerats med befintliga experimentella, analytiska och numeriska metoder för strykande strömning vid låga Machtal på material som används som mottorrumsabsorbenter i lastbilar. Studierna visar att strömnings- och ljudfältet har betydande inverkan på materialets ljudreducerande prestanda. Storleken på strömningsfältets inverkan varierar beroende på vilken av de befintliga analytiska modellerna som används i beräkningarna. Detta tydliggör behovet av kompletterande mer exakta beräkningsmetoder. En ny numerisk metod för att modellera gränsskiktet har utvecklats i detta arbete. Metoden beräknar strömningens påverkan korrekt i jämförelse med Pridmore-Bown på ett beräkningsmässigt effektivt sätt. Den ljudreducerande prestandan för en absorbent i ett strömnings- och ljudfält kan således beräknas med befintliga metoder i kombination med den nya föreslagna metoden. Extra försiktighet krävs när bulkreagerande material behandlas i beräkningarna då detta adderar ytterligare effekter i jämförelse med lokalreagerande material.

Nyckelord: Ljudabsorption, ljudabsorbent, bulkreagerande, gränsskikt, strykande strömning, ljudfält, transfermatris-metoden

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Last but not least, to my family and friends

- Thank you for being there for me in times of joy and doubt!

Anna Färm Stockholm, 29th August 2013

Dissertation

This thesis consists of two parts: The first part gives an overview of the research area and work performed. The second part contains the following research papers (A-D):

Paper A

A. Färm, S. Boij and R. Glav, On Sound Absorbing Characteristics and suitable Measurement methods, Proceedings of the 7th International Styrian Noise, Vibration and Harshness Congress, Graz, Austria (2012).

Paper B

A. Färm, R. Glav R. and S. Boij, *On variation of absorption factor due to measurement method and correction factors for conversion between methods*, Proceedings of the Inter-Noise Conference, New York, USA (2012).

Paper C

A. Färm, S. Boij, *The Effect of Boundary Layers on Bulk Reacting Liners at Low Mach Number Flows*, Proceedings of the 19th AIAA/CEAS Aeroacoustics Conference, Berlin, Germany (2013).

Paper D

A. Färm, O. Dazel and S. Boij *An extended transfer matrix approach to model the effect of boundary layers on acoustic linings*, Submitted for publication, August 2013

Division of work between authors

A. Färm initiated the direction of and performed the studies, made the analysis, the coding and produced the papers. S. Boij and R. Glav supervised the work, discussed ideas and reviewed the work. O. Dazel supervised and discussed the work during a period of the work.

Publications not included in this thesis

Conference paper: A. Färm, S. Boij, P. Göransson, and R. Glav, *On internal mean flow in porous absorbers and its effect on attenuation properties*, Proceedings of the 21st International Congress on Acoustics, Montréal, Canada (2013).

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Part I OVERVIEW



Introduction

This chapter offers basic understanding of the driving forces behind the research performed in this thesis. The incentive for this work is to solve practical development problems in industry applications, however, the research performed is general and independent of application.

1.1 Background

Environmental noise is an everyday pollutant that has increased steadily in society in parallel with the growing use of vehicles. The problem is most clear in urban areas and close to routes of intense traffic. This has led to a strict focus on noise requirements. Not only defining new noise requirements on various kinds of products but also lowering of the sound level limit of acceptance. One area where these lowered noise level limits have had a large impact on the development process is in automotive industry, for example for truck manufacturers. The main contribution to the noise emitted from a truck is generated by the combustion engine and the gearbox. High noise levels are radiated both through the exhaust pipe and through mechanical noise radiated from the engine body and gearbox. The exhaust noise is normally dealt with by designing silencers for the exhaust line and is generally not the main noise problem nowadays. The mechanical noise, however, is still a tough problem to solve and improvement of noise reducing measures needs to be done.

Generally, when facing the challenge of reducing noise emissions there are principally four possible measures;

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- 1) reduce the strength of the source,
- 2) attenuate the noise while propagating,
- 3) shield the source, or
- 4) shield the receiver.

Noise reducing measures are often combinations of the three latter techniques since reducing the source strength in many cases is difficult for practical reasons. Reducing the source strength may not always be the most efficient measure in a cost per dB-reduction perspective either. Techniques 3 and 4 prevent the noise from reaching the receiver. Although the noise at the receiving point is reduced, the total energy in the noise itself is not attenuated. Measures 1 and 2 on the other hand reduce the total sound energy by transferring energy into heat through viscous losses. If the aim is to reduce the total sound power emitted from the noise source, for example from a truck, the sound energy must be reduced and not just redirected.

Noise measures on trucks are primarily aimed at reducing exhaust noise and noise emitted from the engine, gearbox and transmission line. Since truck manufacturers often use a modular system an efficient measure is to shield the noise sources. Total encapsulation of the sources is not possible for two reasons; the shielding parts are placed where motion has to be possible and gaps will occur during driving conditions, and the combustion engine produces large amount of heat which has to be evacuated through some apertures in the encapsulation. Due to this, noise will inevitably be radiated; hence the noise has to be reduced to as large extent as possible before it is radiated (i.e., technique 2 above). The classic measure in these situations is sound absorbing linings placed in the noise path, preferably on walls inside the noise cavity (here the engine compartment). This is the methodology used for noise encapsulations on trucks, as shown in figure 1.1. The encapsulation is made out of an impervious screen with absorbing material on the inside in order to both shield and reduce the noise. In order to improve noise reducing performance of the linings in the noise encapsulations, their performance in the present environment has to be possible to predict. This is not a trivial task due to the complex sound and flow field that these materials are exposed to. The sound reducing performance of an absorbing lining is often mistaken to be a material property which it is not. It is a system property since in addition to the material parameters and geometry it depends on the acoustic state. The sound and flow field above the material are two factors that affect the system properties and the ef-

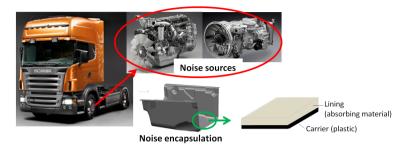


Figure 1.1: General picture of the main noise sources on a truck and the position and layout of ordinary noise encapsulations.

fect of these has to be modelled correctly to obtain accurate predictions of noise reducing performance.

Although one of the factors defining the acoustic state, the sound field, is well-known to affect the acoustic properties of a surface, the importance of this fact and the size of the impact on the absorber is rarely addressed [1]. The two existing experimental methods for determination of acoustic properties of absorbing linings [2, 3] are performed in two different sound fields. The resulting properties therefore differ significantly [4], which is seldome discussed.

The second factor defining the acoustic state that influence the acoustic properties is the flow field creating a boundary layer above the surface. Flow fields in general create boundary layers on surfaces, and grazing flow in particular is a common case for duct applications. The problem of predicting the effect of the boundary layer has been and is being addressed in aircraft industry. There, models of modified boundary conditions on the lining surfaces taking the boundary layer effect into account are being developed [5, 6, 7, 8, 9]. These models are created for locally reacting liners in high Mach number flows. The effect of flow in these cases is clear [10], and the problem with boundary layer effects on sound absorption has commonly been considered as a high Mach number issue. The impact at low Mach number grazing flow on bulk reacting material has not yet been studied and the impact under these conditions is unknown. Present work [11] has shown the importance of including the boundary layer effect on the acoustic properties, giving ground for further analysis and need of methods to handle these factors.

1.2 Objective

The main objectives of this work are to gain insight in how acoustic lining performance is affected by the acoustic state and to develop tools and methods to predict the performance in presence of the factors defining the acoustic state. These methods should be computationally efficient and have a high level of accuracy. They should also be possible to combine with commercial tools such as FEM or BEM to simulate the external noise levels of a running truck. A generic picture of the problem is given in figure 1.2. The first step in this work is to identify which factors in the acoustic state and which material factors that affect the sound absorption and to what extent. After identifying this, suitable numerical methods for the relevant factors are developed. Existing models and methods are applied to evaluate their accuracy and applicability and to see if and where additional methods are needed.

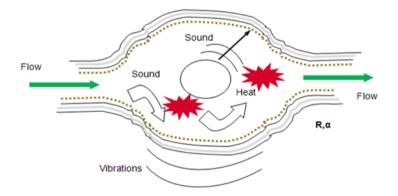


Figure 1.2: Generic picture of the application; complex sound field, flow field and temperature variations in a semi-closed space covered with absorbing material.

The impact of the type of sound field on the acoustic performance is analysed both analytically and experimentally to determine its relevance. The modelling of the effect of this on the absorption properties is today satisfactory and the focus is on stressing its importance and verifying the difficulty of accurate measurements.

Special focus in this thesis is on the modelling of the effect of boundary layers developed at the surface in presence of grazing flow. There is extensive research on-going in this area, both numerically and exper-

imentally and finding a simple yet correct method to predict this effect is of large importance.

Development of measurement methods to verify the effect of flow and sound field is also desirable. This will be addressed in future work.

1.3 Scope

The effect of the sound and flow field on the acoustic properties are analysed for porous sound absorbing material without covering sheets of plastic or perforated plates. Plane sound waves at angles of incidence between 0 and 180 degrees are being studied with grazing flow above the surface. The study is made for low Mach number flows (M < 0.2) in the frequency range 50 - 5000 Hz. The material is modelled as an isotropic and homogeneous equivalent fluid [12] above a rigid wall and the air flow is assumed incompressible and inviscid.

Existing measurement methods are used when applicable to show agreement with theory. Development of new measurement methods including flow are discussed, however, that development falls outside the scope of this thesis.

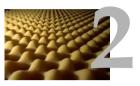
1.4 Long term goal

A future goal for the truck manufacturers is for the noise encapsulation to be multifunctional; not only reducing sound but improving engine cooling and reducing aerodynamic drag simultaneously. This goal is perfectly in line with the ECO²-aspects of multi-functional design; several conflicting vehicle functions are addressed in the design process for this product.

The first step in this development is to have a complete model describing the performance of the absorbers in the present environment to enable optimization of noise treatments for their specific application. This is the aim of this licentiate thesis work. When optimization of the sound reducing performance of the noise encapsulation is possible, the product can also be optimized for other purposes in a virtual environment without the use of time consuming and expensive measurements on prototypes. The shape of the encapsulation can be changed in order to reduce aerodynamic drag underneath the truck, and the cooling flow inside the engine compartment can be more efficient due to the interior

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layout of the encapsulation, guiding the cooling flow. All these properties can be optimized in simulation tools and the noise encapsulation will then enhance noise, cooling and drag performance all at once contributing to a quiet, strong and energy efficient truck.



Absorbing materials

There is a large variety of sound absorbing materials available for the purpose of reducing sound, for example porous materials. These types of materials are commonly used and exist in many variations; from fibrous lumped absorbers to plastic and metallic foams. This variety has been developed to fulfil the need on the market for the large range of applications, demanding different performance and properties from the material. Requirements on, e.g., low flammability, simple cleaning and light weight, are often present at the same time as the requirement for noise reduction. Examples of sound absorbing material are shown in figure 2.1.



Figure 2.1: Three examples of sound absorbing material: a porous plastic foam, a fibrous lumped material and a metal foam.

Common for all materials are nevertheless that sound is reduced by transfer of sound energy by viscous losses into heat. In this work, plastic porous foam is used where the viscous losses occur as the sound waves propagate through the material pores. To predict the losses in the material, a suitable material model describing the wave propagation and at-

tenuation is chosen. The model parameters are in this work determined experimentally. The obtained attenuation depends on material parameters, the amount of material and the acoustic state. The latter will be discussed in chapter 3.

2.1 Material models

Numerous material models of different complexity have been developed to describe sound absorbing materials. The models consider the wave propagation in the material, how the waves are attenuated and refracted. There is a great variety in complexity; from detailed modelling of fibrous materials taking the micro structure into account [13], to porous material with waves both in the air, the frame and combination of these [14, 15], to equivalent fluids where the absorber is described as a fluid with losses incorporated as a the complex wave number [12].

The choice of material model is based upon the behaviour of the material, the purpose of the modelling and the level of detail requested. This choice sets constraints on what results that can be obtained and the accuracy of the results are obviously related to this. In the present work, the Equivalent Fluid Model, EFM, will be used for the absorber. This choice is well grounded since the materials to be analysed are simple porous homogeneous foams without the influence of frame vibrations etc. The EFM by Delany and Bazley [12] is a semi-empirical model of a sound absorbing material 1 . The material parameter needed in this model is the flow resistivity, σ , and the material is described by

$$Z = Z_0(1 + 0.057X^{-0.754} - i0.087X^{-0.732})$$
(2.1a)

$$k = \frac{\omega}{c_0} (1 + 0.0978X^{-0.7} - i0.189X^{-0.595})$$
 (2.1b)

where Z and Z_0 are the characteristic impedance of the absorber and air respectively, k is the wave number in the absorber, c_0 is the speed of sound in air and ω is the angular frequency. The dependent variable X is given by

$$X = \frac{\rho_0 f}{\sigma},\tag{2.2}$$

¹This model was originally made for fibrous absorbers, since the large amount of measurements in their work was made on fibrous material. However, the model has shown to be valid for porous absorbers as well. Other versions of the model has been developed [16].

where ρ_0 is the density of air and f is the frequency. The model is valid for 0.01 < X < 1.0. The flow resistivity is determined through measurements which are described in section 2.1.1

In an in-viscid fluid, and hence also in an equivalent fluid, only longitudinal pressure waves are present. These may be written as harmonic variations of the acoustic pressure as in equation (2.3),

$$p = Ae^{i(\omega t - k_x x - k_z z)},\tag{2.3}$$

where A is the amplitude of the wave, and k_x and k_z are the wave numbers in the x- and z-direction, according to figure 2.2. The acoustic pressure and particle velocity are related by Euler's equation of motion as

$$u_x = \frac{k_x A}{\rho_0 \omega} e^{i(\omega t - k_x x - k_z z)}.$$
 (2.4)

The material parameters are equal in all directions since the material is assumed to be isentropic and homogeneous, thus the wave number in the material is equal in all directions. The losses are included in the complex wave number, where the imaginary part represents the attenuation.

The wave propagation in some material behaves in ways that enables simplification in the modelling of the material. A commonly applied simplification is the assumption of local reaction. The wave propagation is restricted to the direction normal to the surface when making this assumption. Local reaction is further discussed in the modelling section 2.1.2.

2.1.1 Flow resistivity

Porous materials such as plastic foams and fibrous material consist mainly of air saturating the elastic frame of the material. The ratio of the volume of air to the total volume of the material is called the porosity of the material, ϕ . The porosity of sound absorbing materials is often in the range $0.9 \le \phi < 1$. The attenuation inside the material is determined by the viscous losses arising when the air is moving through the pores where the material parameter describing this is the flow resistivity. The flow resistivity is defined as the ratio of the pressure difference across the sample, Δp , to the flow velocity, V, trough the sample normalized by the sample thickness, d, as seen in equation (2.5).

$$\sigma = \Delta p / (Vd) \tag{2.5}$$

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The flow resistivity has the unit Nm⁻⁴s or Rayls/m. It can be determined experimentally according to standardised methods [17] by controlling the flow velocity through a sample and registering the pressure difference across the sample.

The flow resistivity obtained from the measurement is not valid for conditions different from the measurement setup. Alterations in temperature or humidity affect the air properties and hence it also changes the properties of the absorber. Another factor that has been shown to affect the porous material properties is air flow inside the material [18, 19]. The flow resistivity is experimentally shown to increase in the presence of mean flow. This is shown to affect the acoustic surface properties [20] even at very low flow speeds. The flow inside the material is indeed an interesting factor to include in the analysis, however, the existence of this phenomenon is very unlikely in the application considered in this work. Hence, the effect of flow in the material is not included in the present work.

2.1.2 Local reaction

Full modelling of some materials may not be required to obtain correct results and therefore simplifications are possible. One such simplification is the assumption that the material is locally reacting. The simplification implies that the reaction in the material only occur normal to the surface. The reaction in each point is hence independent of the reaction in the neighbouring points since no reacting waves propagate parallel to the surface. The assumption can seem crude; however, in many applications it is justified. An example of materials experiencing local reaction are honeycomb structures with pores normal to the surface, material with fibres normal to the surface or materials having a sound speed much lower than in air. A locally reacting material is illustrated in figure 2.2 together with an example of a honeycomb structure.

The surface properties of locally reacting surfaces have certain characteristics that distinguish them from material with bulk or extended reaction; the surface impedance of a locally reacting surface is independent of the angle of incidence (as will be discussed in section 4.2.1).

2.1. MATERIAL MODELS

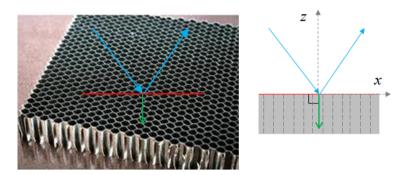
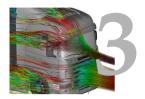


Figure 2.2: A honeycomb-structured absorber material acts locally as illustrated. The transmission angle is always perpendicular to the surface.



Acoustic state

This chapter gives an introduction to factors other than the material properties described in chapter 2 that influence the properties of an acoustic lining. These factors together determine the acoustic state. Analytical models as well as experimental methods to determine the influence of the acoustic state are also described. Finally, a newly developed numerical method to determine the influence of grazing flow is described as an alternative to existing analytical models.

3.1 The sound field

The type of sound field interacting with the material is one part of the acoustic state that always needs to be taken into account in both experimental determination and in simulations. The sound field is in many applications complex and built up from several sound waves interacting with different intensities and directions (see figure 3.1).

Plane sound waves incident from angles, θ , between zero and 180 degrees on a flat lining material are studied in the analytical and numerical part of this work. In addition, a diffuse sound field, built up from superposition of waves incident from arbitrary directions is studied in the experimental part. The absorption coefficient for an ideal diffuse field, α_{rand} , where all angles of incidence are equally probable is obtained as

$$\alpha_{rand} = \int_0^{\pi/2} \alpha(\theta) \sin(2\theta) d\theta. \tag{3.1}$$

where $\alpha(\theta)$ is the absorption coefficient for a certain angle of incidence. The ideal case of a diffuse field is seldom reached in reality and weight-

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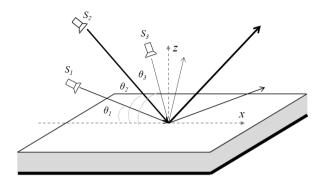


Figure 3.1: Sound field created by three sources with strength S_i and angle of incidence θ_i .

ing factors for the probability of the incidence angles can be used in the kernel to account for this.

The fact that the type of sound field interacting with the absorber affects the obtained absorption properties of the lining is derived from the altered propagation path of the waves inside the material. The change in path length in a medium with losses results directly in a change in absorption.

The modelling and measurements of the surface properties including the effect of the type of sound field are described further in section 4.

3.2 The flow field

The change of acoustic surface properties due to grazing flow has been extensively studied in aircraft industry, both numerically and experimentally [7, 8, 9, 10, 21]. This topic is often addressed for acoustic liners in turbo engines, where the Mach numbers, M, are high and the liners are locally reacting. Since most research on the flow effects have been performed in that research area, the effect of flow is often seen as a high Mach number issue. One part of the present work is to examine if the flow has a significant effect on the surface properties also at low Mach number flows. Another part is to look at the methods to predict the impact of the boundary layer and suggest alternative methods. The impact of the grazing flow differs between bulk and locally reacting surfaces and this is examined within this work as well. A schematic drawing of the mean flow profile in a boundary layer of thickness δ is given in

figure 3.2.

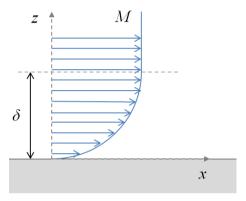


Figure 3.2: Boundary layer of thickness δ developed above the surface due to grazing flow of Mach number M.

Prediction of the impact of the boundary layer on the surface properties can be made either analytically or numerically. Both these approaches are discussed in the following sections. The analytical methods are developed within the aircraft industry and are based on deriving a modified surface impedance, Z_{mod} , from the original surface impedance, Z_s . The numerical methods derive the impact of the flow by calculating the propagation inside the boundary layer itself by discretization. The resulting impact is determined and results are shown in chapter 5.

3.2.1 Existing analytical models

Since the late 1950's, starting with Ingard [5], attempts have been made to predict the acoustic properties of a surface exposed to flow.

The surface impedance without flow is simply obtained by stating continuity in acoustic pressure and normal acoustic particle velocity (or equivalently normal particle displacement) at the surface. Continuity in particle displacement and velocity at the surface is not equivalent in the presence of flow imposed by the discontinuity in the mean flow. A first attempt was made by Myers [6] stating that the boundary layer is infinitely thin and assuming continuity in normal displacement over the vortex sheet. This was for a long period the only used model to account for flow effects, and it is still used in many cases today. The model has in recent measurements [21], however, been proven to erroneously pre-

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dict the flow effects. The model also induce numerical difficulties due to the assumption of an infinitely thin vortex sheet. New models for the boundary layer effects, taking the boundary layer thickness and the flow profile into account, has been developed by Rienstra and Darau [9], Brambley [7] and Aurégan et. al [8]. To account for a boundary layer of non-variating thickness the Transfer Matrix Method will be used and further developed in this work (see section 3.2.2 and 4.2).

3.2.2 Existing numerical methods

The Transfer Matrix Method, TMM, is an efficient numerical tool to calculate transmission and absorption characteristics of single and multi-layered structures. The method will in this work be used to calculate the material properties and to model the flow effects. The flow effects will principally be calculated in two ways; either by using TMM to include the existing analytical models (section 3.2.1) in an interface matrix or to discretize the boundary layer and calculate the wave propagation.

Interface matrix

A so called interface matrix will be introduced to represent the different boundary layer models described in section 3.2.1 in a way that is compliant with the TMM. The interface matrix relates the surface impedance with and without flow as

$$\begin{bmatrix} p_{mod} \\ v_{mod} \end{bmatrix} = \begin{bmatrix} IM_{11} & IM_{12} \\ IM_{21} & IM_{22} \end{bmatrix} \begin{bmatrix} p_s \\ v_s \end{bmatrix},$$
(3.2)

where $Z_s = p_s/v_s$, $Z_{mod} = p_{mod}/v_{mod}$, the surface without flow i represented by s and mod the surface with flow. The acoustic pressure is denoted p and the particle velocity normal to the surface is denoted v. The interface matrices for the different models are given in paper C.

Piece-vice constant flow

The transfer matrix for a multi-layered structure is derived simply by multiplying the transfer matrices, T_i , of all N incorporated layers as

$$T_{tot} = \prod_{i=1}^{N} T_i,\tag{3.3}$$

where T_{tot} is the transfer matrix for the entire structure relating the acoustic state S on both sides of the structure.

This method will be used to model the propagation inside the boundary layer by discretizing it into sub-layers, as shown in figure 3.3. Each sub-layer in this existing numerical method represents a thin piece of the boundary layer with constant flow velocity, M_i , and constant parameters; these layers will here-on be denoted parametric sub-layers.

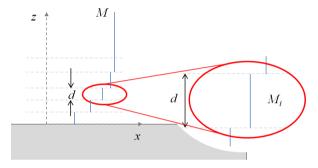


Figure 3.3: Discretization of the boundary layer in to parametric sub-layers of thickness *d*, using piece-wise constant flow velocity with the Transfer Matrix Method.

The transfer matrix for the boundary layer is determined from equation (3.3) and the effect of the boundary layer is included by replacing the interface matrix in equation (3.2) with the transfer matrix T_{tot} .

3.2.3 New numerical method

An extension to the classic TMM has been developed within this work, and is here called eTMM. The method is extended to include gradients of a parameter inside each parametric sub-layer in the discretization. The varying parameter is in this case is the flow velocity, and hence the gradient of the flow velocity in the z-direction is included inside each parametric sub-layer. This inclusion of the velocity gradient is shown to be essential in order for the numerical scheme to converge to the correct solution (compare with the discretization using classic TMM) as shown in paper D [22].

The eTMM is derived using the Stroh formalism [23] where the propagation in the material is described by a set of first order equations as

$$\frac{\partial}{\partial z}[S] = -[A][S]. \tag{3.4}$$

where A is the matrix describing the system (see equation (3.6)), relating the state variables and its derivatives. The transfer matrix is obtained from the A-matrix as

$$[T] = expm([A]d) \tag{3.5}$$

where A is constant through the thickness d of the layer. The governing equations for the fluid (continuity of mass and the linearized Navier-Stokes equations) define the A-matrix for an inviscid and incompressible fluid as

$$A = \begin{bmatrix} 0 & -i\rho(Vk_x - \omega) \\ -i\frac{c_0^2k_x^2 - (\omega Vk_x)^2}{\rho c_0^2(\omega - Vk_x)} & \frac{k_x}{\omega - Vk_x} \frac{\partial V}{\partial z} \end{bmatrix}.$$
 (3.6)

The A-matrix can be determined in every point z in the boundary layer for a known velocity profile V(z). To convert the A-matrix to the final transfer matrix, T, an A-matrix representing the entire parametric sub-layer needs to be derived. To find a representative value for the A-matrix when it is varying through the layer is the key of this new numerical method. The representative A-matrix can be found by evaluating the A-matrix in one or several points inside the parametric sub-layer. In this section, the one point approximation (1p) is shown¹.

In the one point approximation, the *A*-matrix is evaluated in the middle point of each parametric sub-layer, as shown in figure 3.4. The flow velocity gradient and the flow velocity in the middle point is known from the velocity profile and the *A*-matrix in that point is hence known. This *A*-matrix represents the entire parametric sub-layer and can be converted in to the transfer matrix for the layer through equation (3.5). The interface matrix for the boundary layer is obtained by matrix multiplication in the same way as for the TMM in equation (3.2).

3.3 Other factors

There are several other parameters except from the flow and sound field that influence the absorption of the material. These will be omitted in this work, since they are outside of the scope, however, they might be of interest in future investigations.

¹More details and this method and another three point approximation (3p) are shown in paper D.

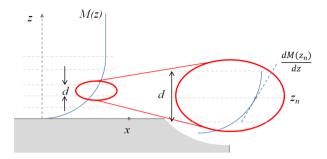


Figure 3.4: The one-point approximation of the *A*-matrix includes the flow velocity gradient $\frac{dM}{dz}$ in the middle point of the parametric sub-layer of thickness *d*.

The temperature field in the cavity and above the material affects the sound field and also the acoustic surface properties. In the engine compartment of a truck, high temperatures are present and the effect of this factor on the surface properties is of interest, and will be studied in future work.

The backing behind the material layer also highly affects the surface properties. The backing is in this project assumed to be rigid and acoustically impervious. Experimental studies of the transmission loss and mode shapes of the noise encapsulation has shown that this assumption may not always hold [24]. The effect on the surface properties when the boundary conditions of the backing are changed is an interesting feature to study.

4 Acoustic absorption

The acoustic properties of an acoustic lining are system properties that are determined through knowledge about the material (chapter 2), the amount of material and the acoustic state (chapter 3). The relevant acoustic properties of the surface of an acoustic lining are introduced and defined in this chapter. The determination of these properties is described in the following subsection both numerically and experimentally.

4.1 Definitions

The two acoustic properties of interest in this work are the absorption coefficient, α , and the surface impedance, Z_s . The two properties are related to each other and basically give the same information regarding the attenuation of sound. Which one of the two properties consider at depends on the application of interest and will be further discussed in the following.

The loss of sound power can be expressed by the energy based absorption coefficient defined as

$$\alpha = 1 - \frac{W_{re}}{W_{in}},\tag{4.1}$$

where W_{in} and W_{re} is the incident and reflected sound power, respectively. The absorption coefficient is between 0 and 1 where 1 represents total absorption. This parameter is often stated as a function of frequency as in for example requirements for sound absorbing materials.

CHAPTER 4. ACOUSTIC ABSORPTION

This entity is easily comparable between materials compared to the surface impedance. The absorption coefficient is, however, a rather blunt tool when it comes to simulations and modelling since no information on how individual sound waves are affected in phase and magnitude at the material surface is given. The surface impedance is better suited for this purpose. The surface impedance relates the sound pressure and acoustic particle velocity at the surface of the material as

$$Z_s = \frac{\cos \theta}{\rho_0 c_0} \frac{1 + R}{1 - R'} \tag{4.2}$$

where

$$\alpha = 1 - |R|^2, \tag{4.3}$$

R is the reflection coefficient, ρ_0 the density of the air, c_0 the speed of sound in air, and θ is the angle of incidence.

The absorption coefficient and surface impedance depend on the material properties, the geometry of the material, the sound field exciting the material and the flow field above the material, i.e., they are system properties.

4.2 Modelling and predictions

The acoustic lining material is in this work modelled as an equivalent fluid as discussed in chapter 2. The acoustic properties of the lining are here derived by the Transfer Matrix Method, TMM. The basic principle of the classic TMM [25, 26, 27] lies within the concept of relating the acoustic state, *S*, in two points by a matrix, *T*, as

$$[S]_1 = [T][S]_0,$$
 (4.4)

where

$$[S]_1 = \begin{bmatrix} p_s \\ v_s \end{bmatrix}. \tag{4.5}$$

The boundary condition at the backing of the lining, S_0 , is in the case of a rigid backing $v_0 = 0$. The transfer matrix for a fluid is a 2 by 2 matrix and can be found in the literature [28] and will not be derived here. The surface impedance, Z_s , is obtained directly from the transfer matrix for

given boundary conditions. For the simple case of a fluid in front of a rigid wall, the impedance is obtained from the ratio T_{11}/T_{21} .

To include the effect of the sound field, the transfer matrix is derived for varying angle of incidence. To include the effect of flow, the interface matrix in equation (3.2) is used, either with the modified impedances from section 3.2.1 or for the transfer matrices of the boundary layer in section 3.2.2 and 3.2.3.

4.2.1 Local reaction

The assumption of local reaction discussed in section 2.1.2 simplifies the modelling of the material and infers specific properties to the surface. The main implication is that the surface impedance for a locally reacting surface is independent of the angle of incidence. This obviously simplifies the usage and implementation of the surface impedance as a boundary condition in simulations. The constant surface impedance does however not imply that the absorption coefficient is independent of the angle of incidence since the reflection coefficient is dependent on the incident angle.

4.3 Experimental determination

The surface impedance and the absorption coefficient can also be determined experimentally. The measurement results are not applicable when any of the system parameters are altered compared to the measurement setup.

4.3.1 Sound field

Two standardized methods to determine the sound absorption coefficient exists: respectively at normal [2] and at randomly incident sound waves [3].

The measurement at normal incidence is based on wave decomposition of plane wave propagation in a duct, enabling determination of both surface impedance and absorption coefficient.

The measurement with diffuse field excitation is based on Sabine's formula, relating the reverberation time to the absorption in a room as

$$T_{60} = 0.161 \frac{V}{A_{eq}},\tag{4.6}$$

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where T_{60} is the reverberation time, V is the volume of the room and A_{eq} is the equivalent absorption area of the room. All absorption in the room is assumed to originate from the absorbing material, and the absorption coefficient is hence obtained by dividing A_{eq} with the area of the absorbing material. The result from this measurement is hence an average sound absorption coefficient for the material, without possibility to determine its surface impedance.

An experimental method to determine the surface properties at arbitrary sound field excitation is desirable in order to avoid the limitation of measured data to certain sound fields. This could be obtained by determining the acoustic properties for incident plane waves from all possible angles of incidence. Since linearity applies, sound fields can be added and arbitrary sound fields can be obtained from the measured data. No such measurement method has to the authors knowledge been fully developed and used today. One possible method, based on the work by Allard [29, 30] is the Measurement of Impedance at Oblique Incidence, here called MIO. In this method, the angle of incidence is controlled and changed whereupon the surface impedance is derived from pressure measurements [4]. This method will be further developed in the continuation of this work and the setup is shown in figure 4.1

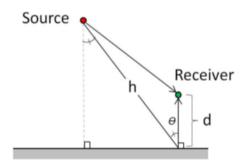


Figure 4.1: Principal sketch of measurement set-up for measuring the surface impedance at arbitrary angles of plane wave incidence, θ . (Note: figure is not to scale, d << h)

4.3.2 Grazing flow field

The flow field above the material affects the acoustic state and the effect of this on the absorption is as mentioned less well known than that of the sound field. No standardized measurement methods have yet been es-

4.3. EXPERIMENTAL DETERMINATION

tablished for this purpose although many methods have been developed and are being used. One common methodology is the so called inverse impedance-eduction methods [31, 32]. The basic principle of these is to perform measurements on a duct and compare the obtained result to numerical simulations, adjusting the surface impedance in the simulations to match the measurement results. These methods are dependent on full knowledge of the sound and flow field inside the duct. Erroneous assumptions on the sound field is one source of errors in this method.

Measurements with flow will be performed in future work.

Effects of acoustic state on absorption

The acoustic surface properties including the acoustic state are presented in this chapter for the general case in figure 5.1 and parameters according to table 5.1, unless stated otherwise. The EFM is valid for the material in the analysis since the parameter X in equation 2.2 is in the valid range $0.01 \le X \le 1$. The surface properties are determined according to chapter 4.

The influence of the two factors of the acoustic state is for clarity shown separately. The effect of the local reaction assumption is also shown, both by itself and it implies for modelling of flow effects.

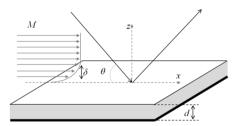


Figure 5.1: General case for which the surface impedance is to be studied with incident plane waves at angles of incidence θ between 0 and 180 degrees and grazing flow at Mach number M. The material thickness is d and the boundary layer thickness is δ .

5.1 The effect of type of sound field

Using the material parameters and the TMM, the absorption coefficient is determined both numerically and experimentally for two different

CHAPTER 5. EFFECTS OF ACOUSTIC STATE ON ABSORPTION

Mach number	Frequency	Boundary layer	Flow
		thickness	resistivity
0.1	3000 Hz	2 cm	5000 Rayl/m

Table 5.1: Parameters used in calculations unless stated otherwise.

sound fields in order to visualise the effect of the sound field. The absorption coefficient was determined experimentally according to standards for normally incident waves and for a diffuse sound field [2, 3] for two porous materials as described in chapter 4. The flow resistivity of the two materials were determined experimentally [17], as seen in table 5.2, and were used as input to the material model in the numerical determination of the absorption coefficient.

Material	Flow resistivity
A	3.5 kRayl/m
В	8 kRayl/m

Table 5.2: Parameters used in calculations unless stated otherwise.

The normal and diffuse sound field absorption coefficients were calculated and are shown together with measured data in figure 5.2.

The absorption coefficient is seen to differ by over 100 per cent depending on the sound field exposing the material. This clearly shows that the absorption determined in one sound field is only valid for that specific sound field.

The same tendency in difference between the absorption coefficient for a diffuse and normal sound field excitation is seen in the results from both measurements and calculations. The largest variation between experimental and numerical data is for the diffuse sound field. This is not surprising since the sound field in the calculations is an ideal diffuse field which is not fully achieved in the measurement. The absorption obtained from the diffuse field measurement in one room is not totally comparable to measurements performed in other rooms due to the difference in sound fields between the rooms. The measured absorption is due to this specific, both concerning the measurement room and the amount and positioning of the material in the room. These three factors contribute to the specific sound field in the room and the probability of sound waves incident from certain angles. The fact that an ideal diffuse field is difficult to obtain in reality has been addressed and examined by

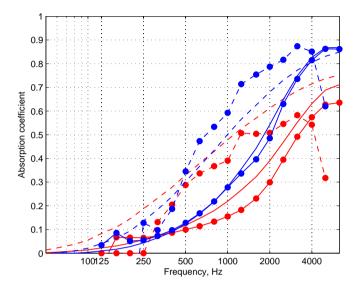


Figure 5.2: Measured and predicted sound absorption coefficient for two porous sound absorbers, A (blue) and B (red), with flow resistivity according to table 5.2 for two sound fields: normal (solid lines) and diffuse field (dashed lines). Measured values are indicated with circles.

e.g. [33, 34]; however, no solution or commonly used method to how to treat this phenomenon has yet been established.

5.2 The effect of grazing flow

Calculating the absorption coefficient in the presence of grazing flow by using the analytical boundary condition models [6, 7, 8, 9] in 3.2.1 shows that absorption can be increased or reduced by as much as 5 per cent with flow at Mach number 0.1 [11, 22]. This effect is not negligible and to obtain correct predictions of the absorption coefficient it must be included in calculations.

The resulting absorption coefficient also differs largely depending on which of the analytical models that is used in the calculations. The difference between the models increases significantly at high Mach number flows and larger boundary layer thickness why the choice of model

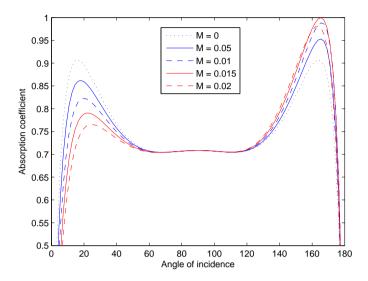


Figure 5.3: Absorption coefficient for a surface of a lining according to table 5.1 exposed to grazing flow of Mach number 0, 0.1, 0.15, and 0.2.

is of great importance for the resulting surface properties (see paper C). To avoid the risk of choosing an incorrect boundary layer model, the eTMM in section 3.2.3 is proposed to predict the boundary layer effect. The eTMM is shown to give correct results compare to the Pridmore-Brown solution and the method is shown to be computationally efficient (see paper D).

The absorption coefficient of a bulk reacting surface exposed to grazing flow for different flow speeds is shown in figure 5.3. The effect of the boundary layer is seen to increase at higher Mach numbers. The character of the effect also changes for increased flow speed: the absorption for waves propagating against the flow is increased and the absorption along with the flow is decreased in addition to the fact that the absorption minima and maxima are shifted to other angles of incidence.

5.2.1 Bulk reacting materials

The effect of grazing flow on the acoustic performance of the surface is easily introduced by multiplication of the interface matrix and the transfer matrix for the material, as described in equation (3.2) in section 3.2. Although this seems simple, errors can be introduced for bulk reacting materials if the transfer matrix or the surface impedance for the material is taken from measurements or calculations without flow. Multiplying the surface impedance with the interface matrix to add the flow effects for bulk reacting materials will not cover the entire effect that is actually added from the grazing flow. The entire effect of the flow on a bulk reacting medium is given by the scattering of the wave inside the boundary layer (modelled by the interface matrix) in addition to the effect of refraction inside the material due to the convective fluid above the material. This will be discussed more thoroughly in the following.

The wave number for waves inside the mean flow at Mach number *M* parallel to the surface for the convective fluid is written as

$$k_{x,conv} = \frac{\omega}{c_0} \frac{\cos \theta}{(1 + M\cos \theta)}.$$
 (5.1)

This wave number determines the refraction at the surface of the absorber according to Snell-Descartes' law of refraction, stating continuity of k_x throughout the structure. The wave number in each parametric sub-layer, i, of the boundary layer in figure 3.3 is written as

$$k_{x,conv,i} = \frac{\omega}{c_0} \frac{\cos \theta_i}{(1 + M_i \cos \theta_i)}.$$
 (5.2)

where M_i is the Mach number in the parametric sub-layer and $\theta_{a,i}$ is the refraction angle inside that layer. The wave number in a quiescent fluid is

$$k_{x,qui} = \frac{\omega}{c_0} \cos \theta, \tag{5.3}$$

which is clearly distinguished from equation (5.1) for a given angle of incidence θ when $M \neq 0$. This is also shown in figure 5.4.

The wave number for the absorber (in equation (5.4)) is the same whether flow is present above the surface or not, resulting in that the refraction angle inside the material, θ_a , differs between the quiescent and convective case.

$$k_{xa} = \frac{\omega}{c_a} \cos \theta_a \tag{5.4}$$

This change in refraction angle affects the surface properties which is shown in figure 5.5 where the absorption coefficient at grazing flow is

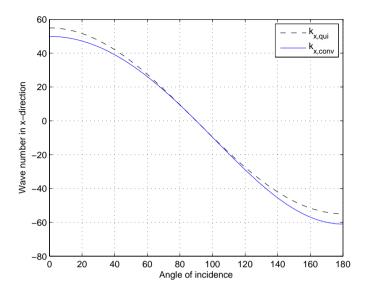


Figure 5.4: Wave number for bulk reacting lining according to table 5.1 with $(k_{x,conv})$ and without the convective effect $(k_{x,aui})$ for M = 0.1.

calculated with the eTMM with the quiescent and convective transfer matrices for the material.

The effect of flow on bulk reacting material is seen to be underestimated if the quiescent wave number is used. When modelling both the material and the boundary layer at the same time this problem is easily avoided. Extra caution has to be taken when the flow effects are to be included numerically on surface properties determined at quiescent conditions. In such cases, the difference in refraction angles can be compensated for by comparing the refraction angles in the quiescent and convective case in equations (5.1) and (5.3). The problem does not occur for locally reacting surfaces since the refraction angle inside the material is independent on the wave number parallel to the surface and the convective effect hence does not affect the material reaction.

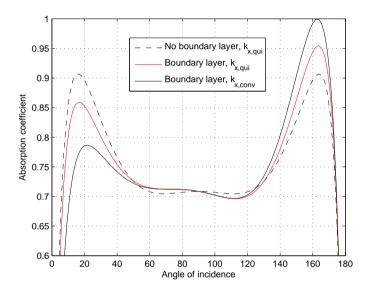


Figure 5.5: Absorption coefficient for bulk reacting lining according to table 5.1 without flow and two cases with grazing flow (M=0.1): using the convective wave number ($k_{x,conv}$) and the quiescent wave number ($k_{x,qui}$).

6 Summary and conclusions

Numerical, analytical and experimental studies have been performed on porous sound absorbing materials to determine the effect on its acoustic performance of grazing flow and the sound field interacting with the material. This chapter summarizes the performed studies with conclusions and main contributions. Investigations planned to continue this research are also suggested.

The three main contribution of this work are:

- Firstly, the development of the new numerical method, eTMM, provides new possibilities to predict boundary layer impact on the performance of sound absorbing linings. The method is fast and correctly determines the acoustic surface properties to a certainty that could not be achieved with the existing analytical methods or numerical transfer matrix methods. The new method also enables the possibility to extend the calculations to include effects of viscosity and gradients in static temperature and density above the lining.
- A second contribution is the knowledge of that flow has to be taken into account in the absorptive properties even at low Mach number flows, and not just at high Mach numbers where most of the research has been done so far.
- The third contribution is the quantification of the impact on the absorption properties of everyday used measurement methods and modelling assumptions. This highlights the usefulness of the continuation of this research topic.

6.1 Conclusions

The acoustic field and grazing flow are both shown to be important factors in the acoustic state to include in calculations to predict surface properties of bulk reacting absorptive linings. The impact of the acoustic field is seen to be as large as 100 per cent for certain cases and the impact of the flow field can be up to 10 per cent even at low Mach number flows. These conclusions are drawn from measurements according to existing methods and calculations according to previously known models.

The influence of the type of sound field interacting with the material was studied with traditional measurement and calculation methods. The absorption coefficient of the absorber varies with the angle of incidence as the propagation length inside the material is altered. The largest impact of the sound field is seen at rather low frequencies and where the absorption is rather small. For example, the magnitude of the difference in absorption between normal incidence and diffuse field excitation was as large as 100 per cent for some frequencies. This emphasises the importance of choosing a measurement method with the same sound field as in the application when testing and specifying the absorptive properties of the material.

A new numerical method has been developed to predict the effect of a boundary layer on the acoustic properties of the surface. The method is based on the discretization of the boundary layer and includes the flow velocity gradients within the boundary layer. The velocity gradients are not included in classic discretization methods, and this is the crucial factor that must be included in order for the predictions to be correct. The new method has fast convergence and is easy to implement. The theory behind the method can in future work be extended to include effects of viscosity inside the boundary layer and gradients of static temperature and density above the lining. The methodology can be used independent of material model used for the acoustic lining.

Numerical studies show that care has to be taken when applying boundary layer effects on the surface properties determined at quiescent conditions for bulk reacting surfaces. The refraction angle inside the lining is changed due to the convective effects and this has to be taken into account. The impact of flow on the surface properties will be underestimated if this convective effect is omitted. This issue does not appear when locally reacting surfaces are considered.

The simplification of the surface as locally reacting is in many cases justified due to the nature of the material. The impact on the surface

properties when falsely introducing this assumption to for example porous or fibrous materials as in this study is significant. The size of the errors depends largely on the sound field exposing the material.

6.2 Future work

A natural continuation of this work is to include viscosity effects and temperature gradients in the new numerical method to evaluate the effect these factors have on the surface properties. Also, the efficiency of the method can be increased by means of more optimized discretization and choice of a optimum position to evaluate the velocity gradient in the boundary layer.

The second and essential continuation of this work is to collect experimental data to verify the numerical findings. Measurements of simple systems through impedance eduction techniques is a good starting point before further development of the promising measurement method MIO is performed.

Influence of temperature gradients on the sound field and propagation through the boundary layer may also be a significant part of the acoustic state to investigate further. In a first step the magnitude of the influence will be evaluated to determine if the impact on the surface properties are significant or negligible.

In performing these studies, better knowledge about factors influencing the performance of the lining is gained and numerical and experimental methods are developed to predict the behaviour. Using these methods will be a powerful tool in the development process in order to optimize noise reduction performance of linings placed in harsh environments.

Summary of appended papers

Paper A - On Sound Absorbing Characteristics and suitable Measurement methods

A. Färm, S. Boij and R. Glav, Proceedings of the 7th International Styrian Noise, Vibration and Harshness Congress, Graz, Austria (2012)

The influence of the sound field and local reaction assumption on the absorption coefficient of an acoustic lining are studied in this paper. Analytical determination of the absorption coefficient was made and showed large variations for both sound field and the local reaction assumption.

Paper B - On variation of absorption factor due to measurement method and correction factors for conversion between methods

A. Färm, R. Glav R. and S. Boij, Proceedings of the Inter Noise conference, New York, USA (2012).

This paper studies the effect of the sound field on the acoustic absorption coefficient of an absorbing lining. The absorption is determined experimentally and analytically for normal and diffuse field excitation. The difference between the absorption for the two sound fields is significant and correction factors between the sound fields are given.

Paper C - The Effect of Boundary Layers on Bulk Reacting Liners at Low Mach Number Flows

A. Färm, S. Boij, Proceedings of the 19th AIAA/CEAS Aeroacoustics Conference, Berlin, Germany (2013).

This paper studies the effect of low Mach number flows on the absorption coefficient of an acoustic lining. The flow effect is predicted with four existing models for this purpose. The models are included in Transfer Matrix Method calculations. The flow is seen to affect the surface properties even at low Mach numbers. The difference between the predicted effect also varies significantly between the existing models.

Paper D - An extended transfer matrix approach to model the effect of boundary layers on acoustic linings

A. Färm, O. Dazel and S. Boij, Submitted for publication, June 2013

Alternative ways to predict the effect of flow on acoustic properties of a surface is studied in this paper. The Transfer Matrix Method was used to discretize the boundary layer and predict its effect. This was shown to give erroneous results why a new extended method was developed. This new method included the gradients of the flow velocity inside the boundary layer which was shown to be essential in order to get correct results. The method had fast convergence and was not computationally heavy.

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Part II APPENDED PAPERS A-D