

Treasure2/FE: A Tool for the FE Simulation of Sound Package Parts Fully Integrated in Nastran

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ABSTRACT

Porous materials are extensively used in the construction of automotive sound package parts, due to their intrinsic capability of dissipating energy through different mechanisms. The issue related to the optimization of sound package parts (in terms of weight, cost, performances) has led to the need of models suitable for the analysis of porous materials' dynamical behavior and for this, along the years, several analytical and numerical models were proposed, all based on the system of equations initially developed by Biot. In particular, since about 10 years, FE implementations of Biot's system of equations have been available in commercial software programs but their application to sound package parts has been limited to a few isolated cases. This is due, partially at least, to the difficulty of smoothly integrating this type of analyses into the virtual NVH vehicle development.

This paper presents a tool, called Treasure2FE, that implements Biot's system of equations and is fully integrated inside Nastran. Treasure2FE allows including in an efficient and flexible way sound package parts into Nastran vehicle FE models used for NVH analyses. All the steps that are necessary to obtain this, in particular the management of the incompatibility between the FE mesh of the sound package part and the FE mesh of the vehicle, are automatically carried out within Nastran.

Furthermore, the tool can be used in conjunction with Nastran ACMS and DMP, to improve computational efficiency.

In this way, the evaluation of the effect of a sound package part on the vibro-acoustic response of a vehicle can smoothly be introduced into virtual NVH vehicle development, making this important type of CAE analysis available to decision-makers.

The paper presents the tool and its functionalities, together with application examples on full-vehicle models up to 500Hz.

INTRODUCTION

Due to their dissipative properties, porous materials are extensively used in automotive acoustics for the purpose of passive noise control; as a matter of fact these materials are, in different forms (fibers, felts etc.), present in almost all sound package parts. Along the years, the issue related to the optimization of their performance/weight/cost has led to the need of models suitable for the analysis of their dynamical and acoustical behaviour and this has generated a considerable research effort devoted to the development of both analytical [5-12] and numerical [13-29] porous material models, all based on the the system of equations initially developed by Biot [2-4]. In Biot's original system of equations, the field variables used to describe the dynamics of the porous material are the displacement fields of its solid and fluid phases. More

recent formulations of the same equations [19-24] use the displacement of the solid phase and the acoustic pressure of the fluid phase as field variables. In all cases, the field variables used are considered to be 'macroscopic', i.e. they represent averages of the corresponding microscopic field variables over a 'control volume' that is assumed to be relatively big when compared to the pores' size and relatively small when compared to the global dimensions of the system under study.

Finite Elements (FE) implementations of Biot's system of equations for the analysis of porous materials have been available in commercial software programs [38-39] for more than 10 years now but, at least until recently, their application was confined to the analysis of small and academic systems (see, e.g., [30-31]). On such systems, these FE software programs have proven many times to be acceptably reliable but, nevertheless, their application for the development of real-life sound package parts was considered only very recently and in very few isolated cases [32-34].

This paper describes first a numerical technology that allows simulating the vibro-acoustic behavior of poroelastic materials (according to Biot's model [2-4]) fully inside Nastran, the FE software package used by many OEMs for their NVH analyses. This numerical technology is based on a few DMAP routines that implement Biot's model using (as much as possible) Nastran native data-blocks and matrices. Simple application examples (taken mainly from the literature) are also described for validation.

In the automotive industry, the main application related to the simulation of poroelastic materials consists in the analysis of the effect that one or more sound package parts can have on the vibro-acoustics of a vehicle body/passenger compartment coupled system. For this application, it is not just necessary to be able to simulate the physical behavior of poroelastic materials, but it is also necessary to develop a 'strategy' that allows not to include directly the FE model of the sound package part(s) into the FE model of the vehicle body/passenger compartment system, since this would be very impractical. Furthermore, one cannot expect that the FE mesh of the sound package part(s) is compatible with that of the vehicle body or of the passenger compartment cavity and so it is also necessary to find a way to deal with the 'problem' of incompatible FE meshes. A procedure for overcoming these issues that allows analyzing the effect of one or more sound package parts in typical NVH FE models used in the automotive industry is outlined in [32]. This procedure is recalled here and it is shown how it can also be fully implemented in Nastran.

The novelty of the approach described in what follows consists essentially (apart from some deep numerical details that could not be reported here) in the fact that it is shown how it is possible to carry out NVH automotive FE analyses including porous materials fully inside Nastran, i.e. without the need to use any external software. This fact has a value, since it helps to guarantee a direct and smooth integration of this type of analyses into the OEM's virtual NVH development process, given that FE analysts can do everything with the tool they are familiar with and that they already have in-house.

FORMULATION OF THE PROBLEM

The problem we intend to analyze is depicted in figure 1 and it involves, from the physical point of view, three separate regions that we will call "domains":

An "elastic domain", i.e. a structure that occupies a volume Ω^e and whose dynamics is governed by the equations of standard linear elasticity [1]. The vibrational state of this structure will be described by a displacement field that we will indicate in what follows with u^e ;

An "acoustic domain", i.e. a limited acoustic space that occupies a volume Ω^a and whose internal acoustic field is governed by the equations of standard linear acoustics [1]. The dynamic state of this acoustic space will be described by an acoustic pressure field that we will indicate with p^a ;

A "porous domain", i.e. a component that occupies a volume Ω^p and whose dynamics is governed by Biot-Allard's equations [2-4,19-22]. The dynamic state of this domain will be described by the couple (u^p, p^p) , the displacement field of its solid phase and the acoustic pressure field of its fluid phase.

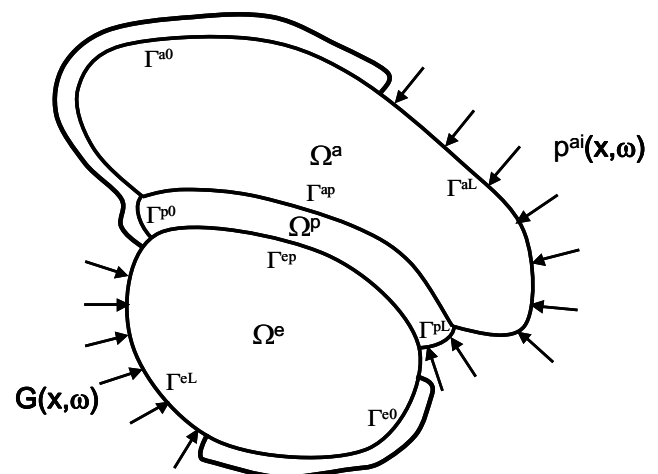


Figure 1 – Schematic representation of the system under study including an elastic, a porous and an acoustic domain with various kinds of boundary conditions and excitations

The boundaries of the different domains will play an important role in the definition of the problem equations. It is then useful to introduce already now the relative notation. We will put:

$$\Gamma^e = \partial\Omega^e \quad \Gamma^a = \partial\Omega^a \quad \Gamma^p = \partial\Omega^p$$

As it is shown in figure 1, we will further assume that the boundaries of the different domains are subdivided as follows:

$$\Gamma^e = \Gamma^{ep} \cup \Gamma^{e0} \cup \Gamma^{eL}$$

$$\Gamma^a = \Gamma^{ap} \cup \Gamma^{a0} \cup \Gamma^{aL}$$

$$\Gamma^p = \Gamma^{ep} \cup \Gamma^{ea} \cup \Gamma^{p0} \cup \Gamma^{pL}$$

where:

- Γ^{ep} is the coupling surface between the elastic and the porous domain;
- Γ^{ap} is the coupling surface between the acoustic and the porous domain;
- Γ^{e0} is a part of Γ^e where the elastic domain is clamped;
- Γ^{eL} is a part of Γ^e where a structural excitation is applied on the elastic domain;
- Γ^{a0} is a part of Γ^a where a rigid boundary condition is assumed;
- Γ^{aL} is a part of Γ^a where an imposed pressure boundary condition is assumed;
- Γ^{p0} is a part of the Γ^p where a constraint is applied (the nature of this constraint will be better defined in paragraph 4);
- Γ^{pL} is a part of Γ^p where an excitation is applied (the nature of this excitation will be better defined in what follows).

As it is apparent from the definitions above, for simplicity we will assume that no direct coupling is present between the elastic domain and the acoustic domain. Furthermore, for the elastic and the acoustic domains, specific possible combinations of boundary conditions/loads are considered and many others are in principle possible. The ones considered here are given just as a typical example, the formulation for the more general case can be found, e.g., in [1].

REVIEW OF THE WEAK INTEGRAL FORMULATION OF THE PROBLEM

Within the following subsections, the weak integral formulations of the dynamic equations of motion for elastic, an acoustic and a porous domain will be briefly reviewed. All these formulations are well known and they are recalled here just for the need of introducing the field

variables that will be used throughout the paper and the corresponding notations. All the equations are formulated in the frequency domain; for the field variables, a harmonic time dependence of the type $\exp(j\omega t)$ is assumed.

WEAK INTEGRAL FORMULATION OF THE EQUATIONS OF MOTION FOR AN ELASTIC DOMAIN

- The weak integral form of the equations of motion for an elastic domain [1] is generally formulated within a suitable subspace of $H_1(\Omega^e)^3$ (the 3-dimensional first order Sobolev space on Ω^e), that physically represents the space of the displacement fields $\mathbf{u}^e$ on the elastic domain that have a finite energy. The detailed definition of this subspace depends on the boundary conditions and on the coupling conditions between the elastic domain and the other domains. Such detailed definition is not relevant here and we will simply indicate this subspace as C^e and we will call it "space of the admissible functions" for the elastic domain.

Given this, the variational formulation for the equations of motion for the elastic domain can be written as follows: for all fixed real ω , find in C^e a displacement field $\mathbf{u}^e$ such that:

$$a^e(\mathbf{u}^e, \delta\mathbf{u}^e) = f^e(\delta\mathbf{u}^e) \text{ for every } \delta\mathbf{u}^e \text{ in } C^e \quad (1)$$

$$a^e(\mathbf{u}^e, \delta\mathbf{u}^e) = k^e(\mathbf{u}^e, \delta\mathbf{u}^e) + j\omega b^e(\mathbf{u}^e, \delta\mathbf{u}^e) - \omega^2 m^e(\mathbf{u}^e, \delta\mathbf{u}^e) \quad (2)$$

$$k^e(\mathbf{u}^e, \delta\mathbf{u}^e) = \int_{\Omega^e} \sigma_{ij}^e(\mathbf{u}^e) \varepsilon_{ij}^e(\delta\mathbf{u}^e) d\Omega^e \quad (3)$$

$$m^e(\mathbf{u}^e, \delta\mathbf{u}^e) = \int_{\Omega^e} \rho^e \mathbf{u}^e \cdot \delta\mathbf{u}^e d\Omega^e \quad (4)$$

$$b^e(\mathbf{u}^e, \delta\mathbf{u}^e) = \int_{\Omega^e} \beta_{ijkh} \varepsilon_{kh}^e(\mathbf{u}^e) \varepsilon_{ij}^e(\delta\mathbf{u}^e) d\Omega^e \quad (5)$$

$$f^e(\delta\mathbf{u}^e) = \int_{\Gamma^e} \mathbf{T}^e \cdot \delta\mathbf{u}^e d\Gamma^e \quad (6)$$

In the formulas here above, the following notations were used:

- σ_{ij}^e is the stress tensor in the elastic domain;
- ε_{ij}^e is the strain tensor in the elastic domain
- ρ^e is the mass density of the elastic domain;
- β_{ijkh} is the damping tensor of the elastic domain;
- $\mathbf{T}^e$ is the stress vector on the boundary of the elastic domain.

Formulas (3), (4) and (5) give respectively the stiffness, the mass and the damping forms associated with the elastic domain. When discretized, these forms give rise to the usual stiffness, mass and damping matrices for an

elastic domain. The functional reported by formula (6) determines the coupling with the external environment and with the other domains.

WEAK INTEGRAL FORMULATION OF THE EQUATIONS OF MOTION FOR AN ACOUSTIC DOMAIN - The weak integral form of the acoustic field equations for the acoustic domain [1] is generally formulated within a suitable subspace of $H_1(\Omega^a)$ (the first order Sobolev space on Ω^a), that physically represents the space of the acoustic pressure fields p^a on the acoustic domain that have a finite energy. The detailed definition of this subspace depends on the boundary conditions and on the coupling conditions between the acoustic domain and the other domains. Such detailed definition is not relevant here and we will simply indicate this subspace as C^a and call it "space of the admissible functions" for the acoustic domain.

Given this, the variational formulation of the acoustic field equations for the acoustic domain can be written as follows: for all fixed real ω , find in C^a a pressure field p^a such that:

$$a^a(p^a, \delta p^a) = f^a(\delta p^a) \text{ for every } \delta p^a \text{ in } C^a \quad (7)$$

$$a^a(p^a, \delta p^a) = \frac{h^a(p^a, \delta p^a)}{\omega^2} - q^a(p^a, \delta p^a) \quad (8)$$

$$h^a(p^a, \delta p^a) = \frac{1}{\rho^a} \int_{\Omega^a} \nabla p^a \cdot \nabla \delta p^a d\Omega^a \quad (9)$$

$$q^a(p^a, \delta p^a) = \frac{1}{K^a} \int_{\Omega^a} p^a \delta p^a d\Omega^a \quad (10)$$

$$f^a(\delta p^a) = \frac{1}{\omega^2 \rho^a} \int_{\Gamma^a} \frac{\partial p^a}{\partial n^a} \delta p^a d\Gamma^a \quad (11)$$

In the formulas here above, the following notations were used:

- ρ^a is the mass density of the air that fills the acoustic domain;
- K^a is the bulk modulus of the air that fills the acoustic domain;
- n^a is the outward normal to Γ^a .

Formulas (9) and (10) give respectively the kinetic energy and the compressional energy forms associated with the acoustic domain. When discretized, these forms give rise to the usual kinetic energy and compressional energy matrices for an acoustic domain. The functional reported by formula (11) determines the coupling with the external environment and with the other domains.

WEAK INTEGRAL FORMULATION OF THE EQUATIONS OF MOTION FOR A POROUS DOMAIN - The weak integral formulation of Biot's equations for a porous domain is considered here in its $\{u-p\}$ form, as introduced first in [20] and successively modified in [22]. In this formulation, the field variables used to describe the porous domain dynamics are the displacement u^p of the porous material's solid phase and the acoustic pressure p^p of its fluid phase. This formulation is generally written within a suitable subspace of $H_1(\Omega^p)^4$ (the 4-dimensional first order Sobolev space on Ω^p), that physically represents the space of the $\{u^p, p^p\}$ fields that have a finite energy. The detailed definition of this subspace depends on the boundary conditions and on the coupling conditions between the porous domain and the other domains. Such detailed definition is not relevant here and we will simply indicate this subspace as C^p and call it "space of the admissible functions" for the porous domain.

Given this, the variational formulation for the equations of motion for the porous domain can be written as follows: for all fixed real ω , find in C^p a displacement-pressure field $\{u^p, p^p\}$ such that:

$$a^p(u^p, p^p, \delta u^p, \delta p^p) = f^p(\delta u^p, \delta p^p) \text{ for every } (\delta u^p, \delta p^p) \text{ in } C^p \quad (12)$$

where

$$a^p(u^p, p^p, \delta u^p, \delta p^p) = a^{p,s}(u^p, \delta u^p) + a^{p,f}(p^p, \delta p^p) - c_1(u^p, p^p, \delta u^p, \delta p^p) - c_2(u^p, p^p, \delta u^p, \delta p^p)$$

$$a^{p,s}(u^p, \delta u^p) = k^{p,s}(u^p, \delta u^p) - \omega^2 m^{p,s}(u^p, \delta u^p) \quad (13)$$

$$k^{p,s}(u^p, \delta u^p) = \int_{\Omega^p} \sigma_{ij}^p(u^p) \varepsilon_{ij}^p(\delta u^p) d\Omega^p \quad (14)$$

$$m^{p,s}(u^p, \delta u^p) = \int_{\Omega^p} \tilde{\rho}^p u^p \cdot \delta u^p d\Omega^p \quad (15)$$

$$a^{p,f}(p^p, \delta p^p) = \frac{h^{p,f}(p^p, \delta p^p)}{\omega^2} - q^{p,f}(p^p, \delta p^p) \quad (16)$$

$$h^{p,f}(p^p, \delta p^p) = \frac{\phi^2}{\rho^{22}} \int_{\Omega^p} \nabla p^p \cdot \nabla \delta p^p d\Omega^p \quad (17)$$

$$q^{p,f}(p^p, \delta p^p) = \frac{\phi^2}{R} \int_{\Omega^p} p^p \delta p^p d\Omega^p \quad (18)$$

$$c_1(u^p, p^p, \delta u^p, \delta p^p) = \alpha \int_{\Omega^p} \nabla p^p \cdot \nabla \delta u^p d\Omega^p \quad (19)$$

$$c_2(u^p, p^p, \delta u^p, \delta p^p) = \beta \int_{\Omega^p} p^p \nabla \cdot \nabla \delta u^p d\Omega^p \quad (20)$$

$$f^p(\delta \mathbf{u}^p, \delta p^p) = \int_{\Gamma_p} \mathbf{T}^p \cdot \delta \mathbf{u}^p d\Gamma^p + \int_{\Gamma^p} \phi(\mathbf{u}^{p,f} - \mathbf{u}^p) \cdot \mathbf{n}^p \delta p^p \quad (21)$$

In the formulas here above, the following notations were used:

- σ_{ij}^p is the stress tensor in the solid phase of the porous domain in vacuo;
- ε_{ij}^p is the strain tensor in the solid phase of the porous domain in vacuo;
- ϕ is the porosity of the porous material that constitutes the porous domain;
- $\tilde{\rho}^p$ is the effective mass density of the solid phase of the porous domain;
- ρ_{22} is the effective mass density of the fluid phase of the porous domain;
- R is the effective bulk modulus of the fluid phase of the porous domain;
- α is the inertial coupling factor between the solid and the fluid phase of the porous domain;
- β is the elastic coupling factor between the solid and the fluid phase of the porous domain;
- $\mathbf{T}^p$ is the total stress vector acting on the boundary of the porous domain;
- $\mathbf{u}^{p,f}$ is the displacement of the fluid phase of the porous domain;
- $\mathbf{n}^p$ is the outward normal to Γ^p .

Formulas (14) and (15) give respectively the stiffness and the mass forms of the solid phase of the porous domain. Apart from the multiplicative coefficient in formula (15), these forms coincide with those of an isolated elastic domain having the same properties of the solid phase of the porous domain in vacuo. Formulas (17) and (18) give respectively the kinetic energy and the compressional energy forms of the fluid phase of the porous material. Apart from the multiplicative coefficients, these forms coincide with those of an isolated acoustic domain having the same properties of the fluid phase of the porous domain. Formulas (19) and (20) define two sesquilinear forms that give the coupling between the solid and the fluid phase of the porous domain. These sesquilinear forms represent the “core” of the Biot-Allard model. The coupling determined by form (19) is of an inertial nature, while the one determined by form (20) is of an elastic nature. It is worth remarking how both these coupling terms are of a volumetric nature.

Eventually, the two terms in functional (21) define respectively the coupling of the solid phase and of the fluid phase of the porous domain with the external environment and with the other domains. As one can see from these formulas, the field variable that naturally couples with the solid phase displacement is the total stress vector acting on the porous domain, while the field variable that naturally couples with the fluid phase pressure is the relative displacement flux between the

solid and the fluid phase, i.e. the so called ‘fluid discharge’ (in the direction normal to the boundary of the porous domain).

DESCRIPTION OF THE COUPLING CONDITIONS BETWEEN DIFFERENT DOMAINS

COUPLING BETWEEN ELASTIC AND POROUS DOMAIN - At the interface Γ^{ep} between the elastic and the porous domain, the following coupling conditions apply:

$$\mathbf{T}^e = -\mathbf{T}^p \quad (22a)$$

$$\phi(\mathbf{u}^{p,f} - \mathbf{u}^p) \cdot \mathbf{n}^p = 0 \quad (22b)$$

$$\mathbf{u}^e = \mathbf{u}^p \quad (22c)$$

The first equation ensures the continuity of the total stress vector at the interface between the two domains. The second equation expresses the fact that the surface of the elastic domain is assumed to be impervious. Eventually, the third equation ensures the continuity of the solid displacement vectors. Applying these equations it is easy to see that:

$$f^e(\delta \mathbf{u}^e)_{\Gamma^{ep}} + f^p(\delta \mathbf{u}^p, \delta p^p)_{\Gamma^{ep}} = 0 \quad (23)$$

This means that the coupling between the elastic domain and the porous domain is natural and only the kinematic condition (22c) has to be explicitly imposed on Γ^{ep} . In an FE implementation, this can be obtained automatically through the assembly of the mesh of the elastic domain and the mesh of the solid phase of the porous domain.

COUPLING BETWEEN ACOUSTIC AND POROUS DOMAIN - At the interface Γ^{ap} between the elastic and the porous domain, the following coupling conditions apply:

$$\mathbf{T}^p = p^a \mathbf{n}^a \quad (24a)$$

$$\frac{1}{\rho_0 \omega^2} \frac{\partial p^a}{\partial \mathbf{n}^a} = ((1 - \phi) \mathbf{u}^p + \phi \mathbf{u}^{p,f}) \cdot \mathbf{n}^p \quad (24b)$$

$$p^a = p^p \quad (24c)$$

The first equation ensures the continuity of the normal stresses across Γ^{ap} . The second equation ensures the continuity between the acoustic displacement and the total porous displacement across Γ^{ap} . Eventually, the third equation ensures the continuity of acoustic

pressure across the same surface. Applying these conditions it is easy to see that:

$$f^a(\delta p^a)_{\Gamma^{ap}} + f^p(\delta u^p, \delta p^p)_{\Gamma^{ap}} = \int_{\Gamma^{ap}} (\rho^a u^p \cdot n^p) d\Gamma^a \quad (25)$$

This equation shows that the solid phase of the porous domain and the fluid of the acoustic domain are coupled through the classical structure-cavity coupling term. In addition to this, the kinematic boundary condition (24c) has to be explicitly imposed on Γ^{ap} . In an FE implementation, this can be done automatically through the assembly of the mesh of the acoustic domain and the mesh of the fluid phase of the porous domain.[^]

APPLICATION OF LOADS AND CONSTRAINTS

LOADS AND CONSTRAINTS ON THE ELASTIC DOMAIN - As already mentioned, we will assume that the part of the boundary of the elastic domain that is not coupled with the porous domain is subdivided into a region where a homogeneous Dirichlet boundary condition is applied (all displacement components equal to zero) and a region where a structural excitation is applied, determined by a surface distribution of forces. This leads to the following conditions:

$$\delta u^e = 0 \text{ on } \Gamma^{e0} \quad (26a)$$

$$T^e = G(x, \omega) \text{ for } x \text{ on } \Gamma^{el} \quad (26b)$$

where G is the function that defines the prescribed distribution of forces.

The parts of the boundary functional (6) related to surfaces Γ^{e0} and Γ^{el} reduce to:

$$f^e(\delta u^e)_{\Gamma^{e0}} = 0 \quad (27a)$$

$$f^e(\delta u^e)_{\Gamma^{el}} = \int_{\Gamma^{el}} G \cdot \delta u^e d\Gamma^e \quad (27b)$$

LOADS AND CONSTRAINTS ON THE ACOUSTIC DOMAIN - As already mentioned, we will assume that the part of the boundary of the acoustic domain that is not coupled with the porous domain is subdivided into a region where a homogeneous Neumann boundary condition is applied (rigid boundary, acoustic displacement equal to zero) and a region where an acoustic pressure is imposed. This leads to the following conditions:

$$\frac{\partial p^a}{\partial n^a} = 0 \text{ on } \Gamma^{a0} \quad (28a)$$

$$p^a = p^{ai}(x, \omega) \text{ for } x \text{ on } \Gamma^{al} \quad (28b)$$

where p^{ai} is the function that defines the prescribed imposed acoustic pressure on Γ^{al} .

As a consequence of (28b), δp^a will be zero on Γ^{al} and the part of the boundary functional (11) related to Γ^{a0} and to Γ^{al} reduce then to zero:

$$f^a(\delta p^a)_{\Gamma^{a0}} = 0 \quad (29a)$$

$$f^a(\delta p^a)_{\Gamma^{al}} = 0 \quad (29b)$$

As a consequence, to obtain the imposed pressure field on Γ^{al} , it will be necessary just to impose just the kinematic condition (28b).

LOADS AND CONSTRAINTS ON THE POROUS DOMAIN - As already mentioned, the part of the boundary of the porous domain that is not in contact with the other domains is subdivided into two regions: a first region Γ^{p0} where a constraint is applied and a second region Γ^{pl} where a load is applied. In general, three different types of constraints are considered: the 'free face' constraint, the 'sliding face' constraint and the 'clamped face' constraint. Similarly, two different types of loads can be envisaged: an imposed displacement and an imposed pressure.

Free-face constraint – A 'free face constraint' applies when a part of the boundary of the porous domain is open to an infinite acoustic medium. In this situation it is assumed that, on this part of its boundary, no support restrains the motion of the poroelastic frame and thus the following conditions apply:

$$T^p = 0 \quad (30a)$$

$$p^p = \delta p^p = 0 \quad (30b)$$

In this situation it is clear that the part of the functional (21) related to Γ^{p0} will reduce to zero. To obtain the 'free face constraint', just the cinematic condition (30b) will have to be imposed explicitly.

It is worth remarking here that conditions (30) exprime an idealization and that they are only approximately satisfied in reality. In fact, since the air surrounding the porous material is of similar impedance as the air in the pores' network, the loading of the surrounding air on the fluid phase of the porous domain will not be negligible. Furthermore, also the loading on the solid phase of the porous domain can be relevant, if the stiffness of the porous frame itself is relatively low.

Clamped-face constraint – A 'clamped face constraint' applies when a part of the boundary of the porous