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► **To cite this version:**

Marie Escouflaire, Stéphane Redonnet. Numerical prediction of absorbing materials via Computational AeroAcoustics. Acoustics 2012, Apr 2012, Nantes, France. hal-00810752

HAL Id: hal-00810752

<https://hal.science/hal-00810752>

Submitted on 23 Apr 2012

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ACOUSTICS 2012

Numerical prediction of absorbing materials via Computational AeroAcoustics

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In the context of reduction of the propulsive noise of airplanes, manufacturers are led to generalize the employment of "sound absorbing materials" (or "liners"), and to optimize their use. The aim of the present study is to improve the numerical prediction of noise attenuation by accurately modelling such absorbing materials either for time domain approaches (such as Computational AeroAcoustics) or for frequency domain methods (such as Boundary Element Method). Such a modelling raises several key questions, which are related to various aspects such as the type of flow involved (heterogeneities, turbulent boundary layers, etc.), the sound levels considered (non-linear phenomena), the diffraction effects induced by ruptures of impedance, etc. Besides specific theoretical developments dedicated to the accurate modelling of acoustic liners, the present work relies on specific calculations, to be compared against other results (analytical, numerical, and/or experimental). Therefore, a numerical campaign has been recently initiated, which aim is to numerically duplicate several canonical tests of noise absorption by acoustic liners. These cases will be used as means of validation to improve the consideration of an accurate acoustic impedance boundary condition for Onera's time and frequency domains solvers.

1 Introduction/Context

The acoustic emission induced by civil aircraft around major airports has become an important societal issue. The effective reduction of such a noise pollution represents both a technical and financial challenge for the aeronautics. Aircraft noise has two main contributors, namely 1) the airframe noise, and 2) the propulsive noise. A way for reducing those noises consists in developing accurate prediction tools, and to integrate them within the design phase of future aircraft programs. Manufacturers then rely more and more on the numerical prediction of the noise phenomena, the latter of which coming along with a better experimental characterization and theoretical understanding of physical mechanisms involved.

Concerning the attenuation of propulsion noise, manufacturers are led to generalize the employment of "acoustic liners", and to optimize their use. Those materials have been applied for a long time to the forward fan noise reduction, by lining in the turbofan nacelles. The tendency is now to extend the integration of these materials within the exhaust in order to attenuate the aft fan noise. This may arise several delicate questions concerning the resistance of these materials in parallel with their acoustical specificities. Indeed, besides their absorbing abilities, these materials must be well adapted to environments such as exhausts that involve severe thermodynamic conditions. An important experimental and numerical research activity was lately devoted to accurately understand the complex mechanisms of absorbing materials.

Within this framework, several studies are conducted with the view of improving the numerical prediction of noise attenuation by the use of absorbing materials. More precisely, the objectives are to accurately model such materials, either for time domain approaches (such as CAA - Computational AeroAcoustics) or for frequency domain methods. Such a modelling raises several key questions, which are related to various aspects such as the type of flow involved (heterogeneities, turbulent boundary layers, etc.), the diffraction effects induced by ruptures of impedance, etc.

The present paper focuses more particularly on the time domain approach. With that view, and besides theoretical developments dedicated to the accurate modelling of acoustic liners, the present work relies on specific CAA calculations, to be compared against experimental results.

Calculations are conducted with the help of Onera's CAA solver *sAbrinA.v0* [5,6], to possibly deal with various

Impedance Boundary Conditions (IBC). Results are then compared to available experimental data.

2 Experiments

2.1 Experimental setups

Two experiments are considered for the validation of the numerical results. The first set of experimental data is given by the NASA/LaRC impedance tube experiment on CT73 material (see below). A second set of experimental data comes from Onera-DMAE's B2A test bench experiments, dedicated to a specific micro-perforated liner. Lately, within this study, this latter material has also been tested on the LAUM (university of Maine, France) impedance test bench.

Besides the provision of experimental data for two very different materials, those three set-ups provide a wide range of different outputs as each bench has its own specificities;

Indeed, B2A bench can deliver bidimensional accurate velocity fields on the entire test cell by Laser Doppler Velocimetry (LDV) measurements. On another hand, both NASA/LaRC and LAUM test benches provide a specific measurement of the pressure on an array of microphones located on the upper wall of the duct. Moreover, the LAUM impedance test bench also offers to study cases with a sound wave propagating with or against the flow; this allows to study the impact of the convection effects of the absorption.

2.2 Tested materials

Two very different families of absorbing materials are considered here. The first one is a ceramic tubular liner called CT73, tested on NASA/LaRC impedance tube [1,2]. This material has a very non linear frequency behaviour. Best absorption is found for that material around 1 kHz for an approximate reactance of 0.

The second material is a specific micro-perforated liner, tested on both DMAE B2A and LAUM benches. The latter material is, on the contrary, linearly behaving on the frequency range of interest (according to Melling's theory on perforated plates [3] if one considers an additional term for the handling of backing cavities).

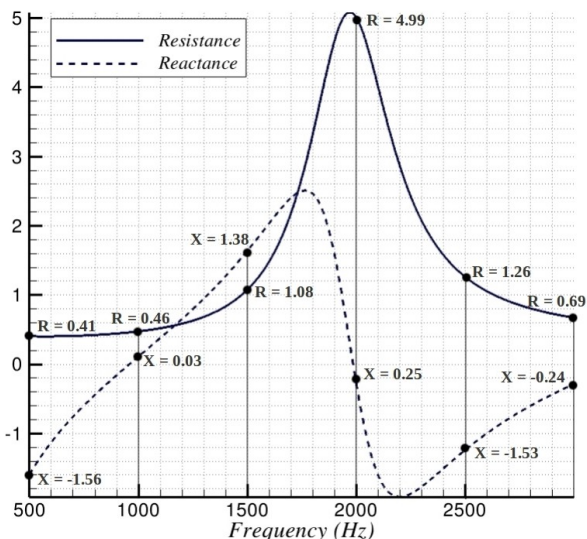


Figure 1: CT73 resistance and reactance experimental data provided fitted with Özyörük's model

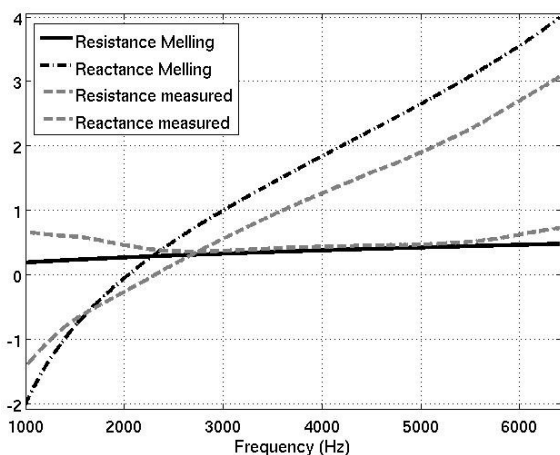


Figure 2: Comparison of the measured impedance of the micro-perforated with Melling's theoretical impedance approach

3 Impedance models

3.1 Numerical approaches

As impedance is a frequency-based concept, it is straightforward to set up an IBC for frequency domain methods. For time domain approaches, numerical impedance models that are still physically representable, are harder to define. The major difficulty is to translate the frequency-based definition of impedance into a time domain notion. As pointed up by Rienstra [4], the physical problem has to remain causal, the variables, real and the acoustically treated wall, passive. Failing in meeting those conditions can easily lead to numerical instabilities.

Several time domain numerical approaches can then be used to describe the behaviour of absorbing materials. Two methods have been studied here. The first one is Özyörük's model (based on the use of filters) which is widely used for frequency broadband applications. It can be very easily extended in the time domain via the so-called Z-transform,

and has seven coefficients (r_1, \dots, r_7) that need to be adjusted (see Eq. (1)).

$$\frac{Z(\omega)}{\rho_0 c_0} = r_1 + \frac{r_2 - r_1}{1 + j\omega r_3} + \frac{j\omega r_4}{(1 - \omega^2/r_6^2) + j\omega r_5} + j\omega r_7 \quad (1)$$

The second one is Rienstra's model [4] which is much closer to the physical Helmholtz resonator analogue (see Eq. (2)).

$$Z_{EHR}(j\omega) = R_f + j\omega m_f - j\beta \cot(\frac{1}{2}\omega T_l - j\frac{1}{2}\epsilon) \quad (2)$$

This second approach is also very accurate to describe a linearly behaving material. Moreover, it is really close to Melling's theoretical model that describes the present micro-perforated material quite precisely.

3.2 Non-linear fitting of the frequency behaviour curves of materials

3.2.1 Description of the method

A method has been set up to identify Özyörük's coefficients in order to fit frequency behaviour curves of the materials. The algorithm is based on the Non Linear Square Fit method, also called Levenberg-Marquardt Algorithm (LMA). The LMA extends the basic least square fitting method to a minimization of non-linear functions using both the Gauss-Newton algorithm and the technique of gradient descent. This method strongly relies on the input guessed values. It has been adapted in order to fit resistance and reactance behaviour curves separately using the specific real and imaginary parts of Özyörük's impedance function (see Eq. (1)). The iterative procedure is initiated with semi random input vectors of solutions (r_1, \dots, r_7) which orders of magnitude are chosen close to the final solution for a faster convergence of the method. The latter also integrates, as an additional constraint, the Rienstra's conditions [4] so that each set of coefficient lead to stable numerical simulations.

Specific actions are under progress in order to improve the accuracy of the fitting method. Among others, it is intended to fit directly the admittance behaviour curves rather than the impedance ones. Indeed, admittance function does not take infinite values at low frequencies such as impedance does. Moreover, the admittance function is more clearly related to the absorption of the material and enables faster comparisons with numerical results.

3.2.2 Application to CT73 material

The fitting method was first applied on NASA/LaRC CT73 material (see Figure 3). This action revealed the non-uniqueness of the LMA solution, which led to study the weights of the coefficients.

Coefficient r_6 appears to be linked to the maximum of the resistance and the inflexion point of the reactance [10], and can be chosen equal to ω for this maximum. A specific and accurate determination of this maximum value during impedance measurements must then be accurately done for such applications.

Coefficient r_1 determines the resistance for low frequencies. In case of multiple local maximums of resistance, the method must then be applied to several portions of the frequency range. The set of coefficients found is then dependent on the frequency frame to be.

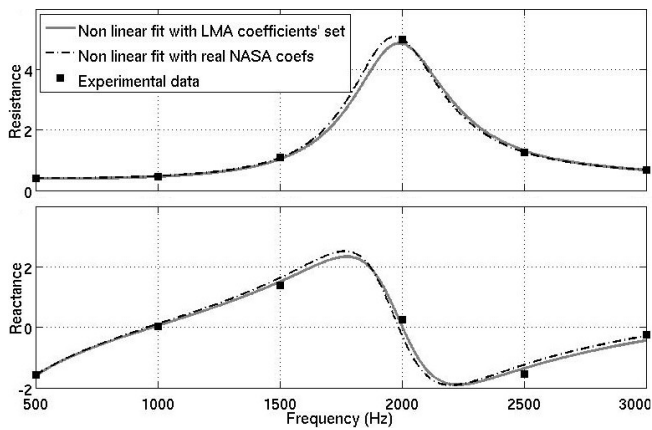


Figure 3: LMA method applied to CT73 material experimental data. Comparison with NASA/LaRC model

Without setting r_6 to a specific value, several sets of coefficients can be found. Despite the fact that some sets seem to lead to a better fitting of impedance curves, it appears that none of them gives better results when CAA-exploited than the one provided by NASA/LaRC. Further investigation will consist in deriving new sets of coefficients with r_1 and r_6 a priori specified.

3.2.3 Extension to the micro-perforated material

For this second material, it is much more difficult to make a good guess of input coefficients as the local maximum of resistance is not clearly determined. All the coefficients are then identified by the LMA algorithm. Several sets may be found, depending on the frequency range considered.

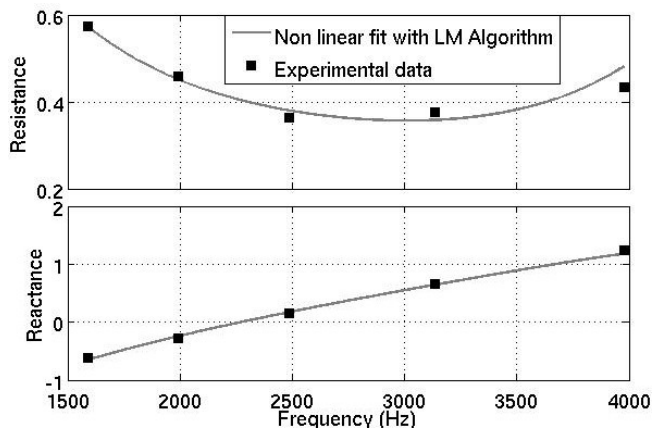


Figure 4: Fitting of the micro-perforated impedance experimental data with Özyörük's numerical model

Without the knowledge of r_6 coefficient, it is difficult to determine a set of coefficients leading to accurate simulation results at all frequencies. Several theoretical and numerical investigations are currently conducted to propose an accurate value of this coefficient and to improve the model.

Thanks to the LAUM experimental behaviour curves data obtained within the present framework, a proper set of coefficients has anyhow been found (see Figure 4). This set has been used for the numerical simulations (see below).

4 time domain simulations via CAA

4.1 The CAA solver *sAbrinA.v0*

The CAA solver *sAbrinA.v0* [5,6], developed by Onera-DSNA, is a structured CAA code solving the full Euler equations, the latter being taken under a conservative/perturbed form. This solving is classically conducted with the help of high-order finite differences (6th order spatial derivatives and 10th order filters), and a Runge-Kutta RK3 time marching scheme. The code deals with multidimensional structured grids, and it offers a wide set of boundary conditions (solid wall reflection, spinning mode excitation, free-field radiation, etc.). Here, one can precise that the plane wave excitation is achieved with the help of a specific source (a monochromatic Gaussian function). This indeed, is preferable to make use of a classical boundary condition, since it allows a better anechoicity of the duct's upstream part.

The acoustic liner IBC relies on a modelling of the admittance $Y(\omega) = Z(\omega)^{-1}$, which is derived from Özyörük's impedance. Its translation into time domain is achieved via a Z-transform, to avoid the handling of expensive convolutions (as would be encountered with a Fourier transform). Myers general impedance condition in the z-domain is given by:

$$\frac{1-z^{-1}}{\Delta t} P(x, z) + u_0 \frac{\partial P(x, z)}{\partial x} = \frac{1-z^{-1}}{\Delta t} Z(z) V_n(x, z) \quad (3)$$

for a flat-wall boundary problem with a uniform mean flow. With a mean sheared flow satisfying the Navier-Stokes equations, the mean velocity is zero at the wall and the term $u_0 \frac{\partial P(x, z)}{\partial x}$ vanishes. The impedance model is:

$$Z(z) = \frac{a_0 + \sum_{l=1}^4 a_l z^{-l}}{-1 - \sum_{k=1}^3 b_k z^{-k}} \quad (4)$$

where a's and b's are identified from the r's of (1).

4.1.1 Previous validations of the IBC

Early validations of the *sAbrinA.v0* IBC [7,8] were based on the CAA-simulations of NASA/LaRC test case. Calculations had been run without flows, as well as with uniform and sheared flows of several Mach numbers.

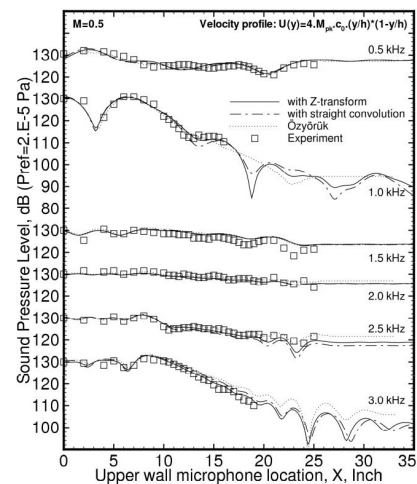


Figure 5: Comparison of Sound Pressure Level for $M=0.5$ with sheared flow velocity profile, Delattre [10]

Those calculations (see Figure 5) had led to several key conclusions. First, the ability of accurately CAA-simulating lined duct was validated with or without flow, over the whole frequency range. It was also shown that the numerical results seemed to be even closer to the experimental data when a realistic sheared flow velocity profile was used.

4.1.2 Influence of the mean flow direction

As an extension of the previous validations, CAA-calculations were here performed again, but for acoustic waves propagating with and against a uniform flow at frequencies between 2,5 and 3 kHz (see Figure 6). It appears that below 2875 Hz, the material absorbs more when acoustic waves propagate against the flow. Beyond this frequency, the material becomes more efficient when acoustic waves propagate with the flow.

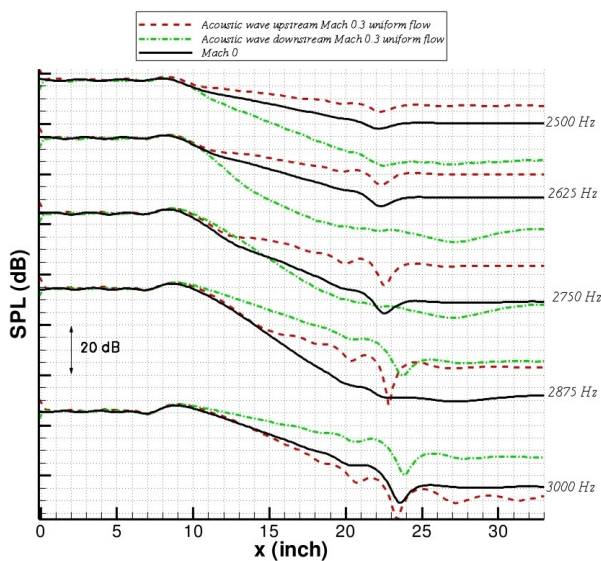


Figure 6: *sAbrinA.v0* results for waves propagating with and against Mach 0.3 uniform flow compared with a no flow case

As recently shown by Renou et al. [9], the direction of the flow has an influence on the transmission coefficient of waves propagating in a lined duct. In particular, the minimum of this transmission coefficient is frequency shifted depending on the direction of flow.

With respect to the cases simulated, transmission coefficients have been estimated by the LAUM (see Figure 7).

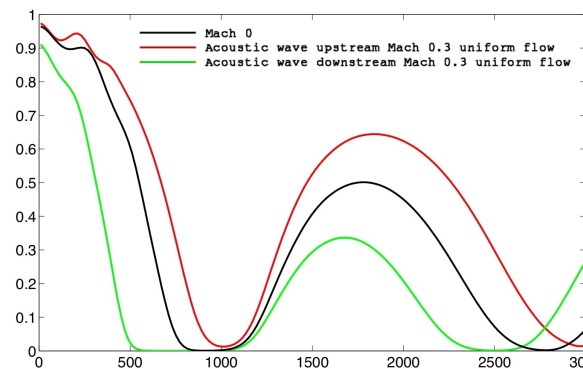


Figure 7: Transmission coefficients calculated for acoustic waves propagating with and against a Mach 0.3 uniform flow - with courtesy of the LAUM

As one can see, the tendency is in good agreement with the CAA results. Those first insights are qualitative but further investigations will be conducted on the micro-perforated material, as recent experiments have been conducted on the LAUM impedance test bench for acoustic waves propagating with and against the flow.

4.2 Early results with the micro-perforated material

The B2A experiment [11]. (with the micro-perforated material) has then been CAA-simulated. Calculations were achieved for the frequencies [1592, 1992, 2488, 3136, 3976] Hz. Best absorption of the material is found around 1650 Hz.

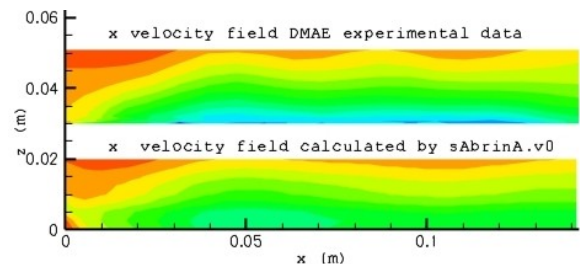


Figure 8: Comparison of x-velocity field in B2A test cell and x-velocity field calculated by *sAbrinA.v0* at 3976 Hz

With best sets of coefficients found via LMA, a good agreement between numerical simulations and experimental data is found for higher frequencies (see Figures 8 and 9). However, around the best absorption frequency, the calculations seem to slightly overestimate the attenuation (especially for 1992 Hz, see Figure 10), even though the global behaviour tendency seems in good agreement with the experimental data.

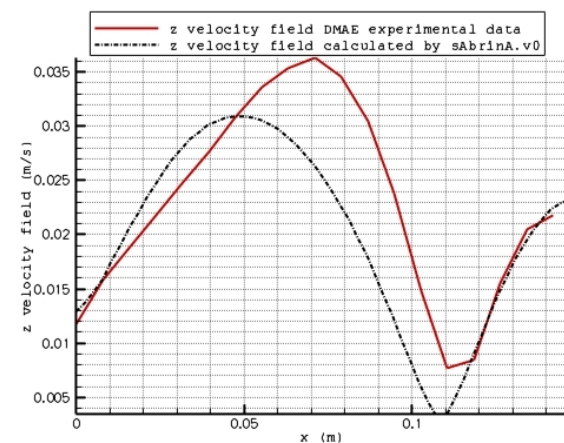


Figure 9: Comparison of z-velocity field in B2A test cell and z-velocity field calculated by *sAbrinA.v0* at 3976 Hz

Indeed, the IBC coefficients derived from the fitting of the micro-perforated material, is likely to be inaccurate for frequencies neighbouring the best absorption one. This is due to the rapid variation of the admittance around the latter. An improvement is expected from a refinement of the fitting method around frequencies of interest, and by the direct use of the admittance function.

Also, a comparison against LAUM impedance test bench experimental pressure data and latest LDV results provided by Onera-DMAE is currently under progress.

Those last measurements covering a greater range of frequencies, such a comparison will complete the numerical validation works.

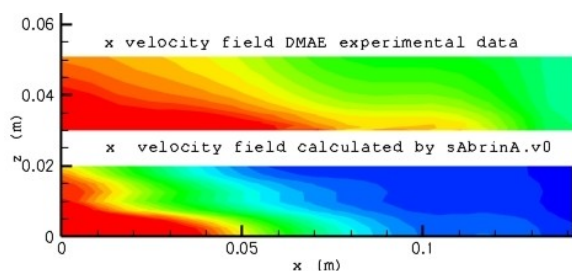


Figure 10: Comparison of x-velocity field in B2A test cell and x-velocity field calculated by *sAbrinA.v0* at 1992 Hz

5 Conclusions and perspectives

The present work concerns the improvement of the absorbing materials' modelling with respect to a time domain numerical approach.

First actions has consisted in extending Özyörük's based IBC (initially tuned from NASA/LaRC CT73), to other types of materials.

This has required to set up a fitting method for determining sets of coefficients that match with any kind of impedance curves. As the fitting solution is non-unique, a study of its sensitivity to the coefficients has been conducted. This has highlighted the importance of the choice of r_1 and r_6 coefficients values, and thus of the accurate characterization of the maximum of impedance during measurements.

With the help of the IBC, NASA/LaRC test case was CAA-computed under particular conditions of flow. In particular, the impact of the flow direction on the acoustic absorption has been examined. Results reveal a difference of absorption whether the acoustic waves propagates with or against the flow, which were confirmed by LAUM experimental results.

B2A test case (with a micro-perforated material) was also computed and compared against experimental data provided by Onera-DMAE. This led to encouraging results, which shall be completed in the near future.

Next steps will consist in improving the fitting method by making direct use of admittance functions, which shall lead to a better accuracy of the coefficients.

Rienstra's model will also be studied and potentially implemented into *sAbrinA.v0* to evaluate its ability to properly describe acoustic absorbing material via a time domain solver.

Also, recent experimental characterizations of the micro-perforated material at the LAUM, CTTM and Onera-DMAE will lead to further cross-comparisons.

Beyond all that, current works are also devoted to the development and application of frequency based IBC with respect to a Boundary Element Method. This shall diversify means of numerical prediction of acoustic liners' effect.

Both the time domain and the frequency domain solvers application and validation to current experiments will be the matter of a future article (submitted to *Internoise 2012*).

Acknowledgments

Yves Aurégan, Ygaäl Renou from the LAUM and Baudoin Gaulin from the CTTM are warmly thanked for their precious help during the experimental campaign set up in Le Mans and for all the very useful comments on the present work.

Estelle Piot, Julien Primus and Frank Simon from Onera-DMAE are also thanked for their ongoing contributions to this work and for all very interesting discussions on the problems encountered.

Grégory Delattre (who developed the CAA IBC) and Daniel-Ciprian Mincu (who helped in implementing it within *sAbrinA.v0* environment) are acknowledged for their indirect contribution to the present study.

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