ERCIM "ALAIN BENSOUSSAN"
FELLOWSHIP PROGRAMME

# Scientific Report

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| Nationality | Czech Republic |
| Name of the *Host Organisation* | Norges teknisk-naturvitenskapelige universitet – NTNU |
| First Name / family name of the *Scientific Coordinator* | U. Peter Svensson |
| Period of the fellowship | 01/03/2017 to 28/02/2018 |

## I – SCIENTIFIC ACTIVITY DURING YOUR FELLOWSHIP

The ERCIM Fellowship gives opportunity to improve scientific skills in the field of mathematics and informatics. My research activities belong to the field of the sound field numerical analysis. The sound propagation can be modelled with plenty of methods which are often divided in wave-based methods and geometrical acoustics.

Research activities conducted under the supervision of Prof. Peter Svensson were related to the edge source integral equation (abbrev. ESIE) and the boundary element method (abbrev. BEM). The edge source integral equation [J. Acoust. Soc. Am. 133, pp. 3681-3691, 2013] decomposes the sound into direct sound, reflected sound, first order diffraction and higher order diffraction. The ESIE calculates the sound pressure in field points for convex and rigid objects. On the contrary, the boundary element method solves the Helmholtz Integral Equation in two steps. In the first step, the acoustic variables (sound pressure and particle velocity) are found on the domain boundary. The domain boundary is segmented into elements and the acoustic variables are calculated in element nodes. The sound pressure in field points is calculated in the second step. Green's function is used for obtaining the direct sound component (i.e. the sound propagation in free field) both in the BEM and ESIE.

The main scientific topic of my ERCIM Fellowship is the hybrid method (the ESIEBEM) which is recently developed numerical method. The ESIEBEM is result of many hours of team work. The team consists of the ERCIM Fellow, Prof. Peter Svensson and Dr. Sara R. Martin. The ESIEBEM is presented in the paper listed below which is currently submitted to The Journal of the Acoustical Society of America. The ESIEBEM obtains the result in two steps as the BEM. In the first step, the ESIE is used for propagating the sound from the sound source to collocation points located in element centers on the domain boundary. The second step makes use of the BEM formulation which calculates the sound pressure in field points. The ESIEBEM described in submitted paper works for scattering problems and triangular elements but it is possible to extend the applicability of this method in the future. The limitation of the ESIEBEM is singularity in the kernel BEM integral which might occur in the second calculation step. It is necessary to implement the near singular integration based on the element subdivision when the receiver is located near to the domain boundary.

The Fellow devoted large amount of time to improve the computational efficiency of the 3D version of the open-source software OpenBEM. The goal of reprogramming several functions was to increase the calculation speed. Increase of the speed was based on restructuring the code and replacing several functions written in Matlab by functions written in C. C functions are compiled as MEX functions and are run within Matlab functions. New version of the OpenBEM is tested towards the original source code and also verified with an analytical solution. Scattering problems can be verified with a sphere test case with the plane wave progressing in the *z*-axis direction and receivers placed in the circle. Vibrating problems can be verified with the zeroth-order pulsating sphere, first-order pulsating sphere and cylindrical vibrating pistion on a spherical baffle. Both 4th version and new OpenBEM version use meshes created by the GMSH software. Meshes can be triangular (contain three nodes per an element) or quadrilateral (contain four nodes per an element).

The Fellow also spent time with the preparation of two publications coauthored by Peter M. Juhl (University of Southern Denmark). These two papers still wait for comments from the coauthor and their date of submission is unknown. The first paper describes the simplified 2D BEM using collocation points which are already implemented in the ESIEBEM. The 2D BEM employs its own meshing function which segments the boundary into linear elements. The collocation point is always situated in the center of the linear element. This formulation speeds up obtaining the 2D BEM solution provided that the user accepts certain approximation. The second paper deals with the fast multipole boundary element method in 2D (2D FMBEM). The Green's function which uses the Hankel's function in 2D is expanded into an infinite series. The coordinate system is rotated and transferred for each element in order to simplify the over-complicated expansion of the Green's function and the Green's function derivative with respect to the vector normal to the boundary. The 2D FMBEM is tested with 2D OpenBEM and with the analytical solution. The analytical solution is calculated with an infinitely long cylinder in the free field.

The author plans to participate in the conference Euronoise 2018 together with five coauthors. The conference paper abstract is submitted and the full paper will be written and submitted after the end of the Fellowship. The paper is focused on the edge-diffraction based modelling with the ESIE method. The hybrid technique mentioned in this report is also used to find the sound pressure on the object's surface. Euronoise 2018 will be organized in May in Crete, Greece.

## II – PUBLICATION(S) DURING YOUR FELLOWSHIP

Submitted papers:

Martin, S. R., Svensson, U. P., Slechta, J., Smith, J. O.: *A hybrid method combining an edge-diffraction based method and the boundary element method for sound scattering calculations*. The Journal of the Acoustical Society of America.

Slechta, J., Svensson, U. P.: *Numerical Techniques for the Assessment of the Environmental Noise Attenuation.* Akustické listy.

Other two publications are currently being prepared in cooperation with Peter M. Juhl (University of Southern Denmark):

- *Simplified Boundary Element Method for Modelling Complex Noise Barrier Shapes*,
- *An Implementation of the 2D Fast Multipole Boundary Element Method for the Noise Barrier Analysis*.

## III – ATTENDED SEMINARS, WORKHOPS, CONFERENCES

(1) Euronoise 2018, Crete, Greece, 27 - 31 May 2018
Accuracy aspects of diffraction-based computation of scattering

Authors: U. Peter Svensson, Sara R. Martin, Jason Summers, Blake Teres, Jan Slechta, Charles Gaumond

Abstract:
*Edge-diffraction based modeling, in the form of the Edge Source Integral Equation (ESIE), [J. Acoust. Soc. Am. 133, pp. 3681-3691, 2013], has proven efficient and accurate for radiation problems such as modeling loudspeakers in convex-shaped rigid enclosures. Some singularity issues have been identified for certain source/receiver positions, and the problem as regards receiver positions can be avoided through a recently suggested hybrid technique [Proc. Meet. of Acoustics. 26, 015001, 2016]. The hybrid technique uses the edge-diffraction formulation to find the sound pressure at the surface of the scatterer, and employs the Kirchhoff-Helmholtz Integral Equation to propagate the surface sound pressure to external receiver points. For these techniques mentioned above, computed*

*results are assumed to converge towards a correct result, and one usually has to use the finest mesh that is computable with the available resources. Such a single computation does, however, not directly indicate the accuracy of the result, but by employing computations for several mesh sizes, a Taylor expansion model of the computation error can offer the possibility for a Richardson extrapolation as a convergence acceleration technique. This technique is well-known for some computation techniques but possibly not so widely known. Here, this technique will be demonstrated for some particularly challenging cases of computing far-field backscattering from compact scatterers with the ESIE method, as well as some other challenging geometries. Pronounced cancellation effects between first- and higher-order diffraction components lead to very high accuracy requirements for the computations, and convergence acceleration turns out to be highly effective.* *[Portions of this material are based upon work supported by the Office of Naval Research under Contract No. N68335-17-C-0336; the Research Council of Norway, project no. 240278; and the ERCIM Alain Bensoussan Fellowship Programme].*