Source models for noise radiation calculations from large structures and industrial plants

F. Augusztinovicz, P. Gajdátsy, F. Márki, P. Fiala and A. B. Nagy
Budapest University of Technology and Economics, Dept. of Telecommunications
H-1117 Budapest, Magyar tudósok körútja 2., Hungary
email: **fulop@hit.bme.hu**

Abstract

The paper summarizes those analytical and numerical models, which can be used to calculate noise radiation from large sources such as civil structures, industrial equipment and plants. Simple elementary sources such as point, line and plate sources are outlined and their sound field compared. A number of numerical methods are also outlined and shortly evaluated from the industrial application's point of view. A case study, dealing with source ranking and quantification of the partial noise sources of a heating plant is discussed in some detail and various calculation methods are compared.

1 Introduction

The modelling and simulation of noise emission and propagation from industrial plants and other large-scale noise sources has earned special attention nowadays, in the wake of an important EU Directive on noise mapping [1]. Well established methods and commercial software packages for the simulation of other major environmental noise sources such as road and rail traffic do exist for quite some time. Other fields, for example aircraft noise and especially industrial noise are still object of scientific research [2], and intensive efforts of harmonizing the existing methods developed for various sources in different countries are currently in progress [2,3].

Noise mapping, as treated in the EU directive and underlying standards and calculation methods (for a exhaustive summary see e.g. [4]) aims at calculating and demonstrating environmental noises in very condensed, graphical form. Such a rough estimation does not require very accurate source models. The aim of this paper is somewhat different: rather than calculating single number time-averaged noise figures as a function of the spatial coordinates for many immission points, we endeavour to develop source models which are apt for determining levels and spectral distribution of noises, radiated from large structures, industrial equipment and plants at a few critical points at medium distance. Potential applications of the models and calculation methods to be discussed are source identification and partial noise source ranking of industrial systems and civil structures, e.g. bridges.

The first part of the paper addresses some very basic radiation models. Based on a case study of a heating plant, it is demonstrated that even very simple source models can reasonably serve the purpose. In the second part a special version of the Boundary Element Method is discussed and the obtained results shown.

2 Analytical models

2.1 Elementary sources: point, line, and plate sources

A usual analytical approximation of real-life sources is to substitute them by elementary volumetric sources of extreme dimensions. The simplest one is the monopole or *point source*, which is the limit value of a source of infinitesimal dimensions in all three directions. If the source is assumed to be nonzero in size in one direction but infinitely small in any other, one gets the approximation of (infinite or finite) *line source.* Another, more realistic approximation of a real source is the flat or *panel source*, being infinitely thin but finite in size in two other dimensions.

Just in order to recall the basics of the radiation theory, assume that a point source of power W is operating in free acoustic field. The sound intensity I, generated at a distance d from the source can be calculated as

$$I = \frac{W}{4\pi d^2} \tag{1a}$$

which yields for the sound pressure L

$$L = L_W - 11 - 10\log\left(d^2\right) \tag{1b}$$

In case of a line source, the energy is distributed along another, smaller surface, hence the intensity I' referring to unity length of line is

$$I' = \frac{W'}{2\pi d} \tag{2a}$$

or

$$L = L_{W'} - 8 - 10\log(d) \tag{2b}$$

where W' stands for power per unit length. It is very important to stress that the equations only hold if the line consists of an infinite number of incoherent point sources, distributed uniformly along the line.

Maekawa has shown in his pioneering paper [5] that (2) is transformed into

$$L = L_{W'} - 11 - 10\log(d) + 10\log\left(\tan^{-1}\frac{l}{d}\right) \tag{3}$$

if the source is of finite length l.

Equations (1b), (2b) and (3) are compared in Fig. 1, by assuming equal sound power values. It is well known that the sound level radiated from a point source reduces with 6 dB/d.d. and from an infinite line source with 3 dB/d.d. It is worth noting, however, that the finite line source also tends to behave as a point source towards higher distances.

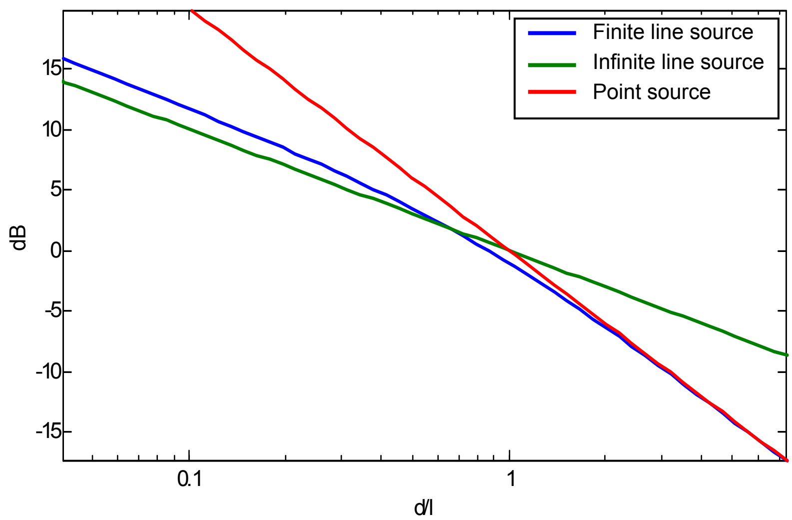

Fig. 1. Comparison of radiated sound pressure levels at distance d from a point, an infinite line and from a finite line source of length l.

If one assumes a vibrating plate of dimensions x_l and y_l and the sound pressure level L is to be calculated at distance d from the plane of the plate, the calculation is somewhat more complex since the obtained integral cannot be solved in closed form. Maekawa has given a first approximate formula for the problem [5], which was further improved and verified by Janaĉek [6]. According to this latter one and assuming a plate of x_l=1, the resulting pressure for plates of identical radiated power but different edge ratios is demonstrated in Fig.2.

Once again, the sound field at large distances tends to be identical with that of a point source of equal sound power. This is obviously the consequence of Huyghens' principle: for large distances any source of finite dimension generates spherical waves, hence the plane-wave-like behaviour of any finite plane source vanishes and the plates behave as a simple source at large distances.

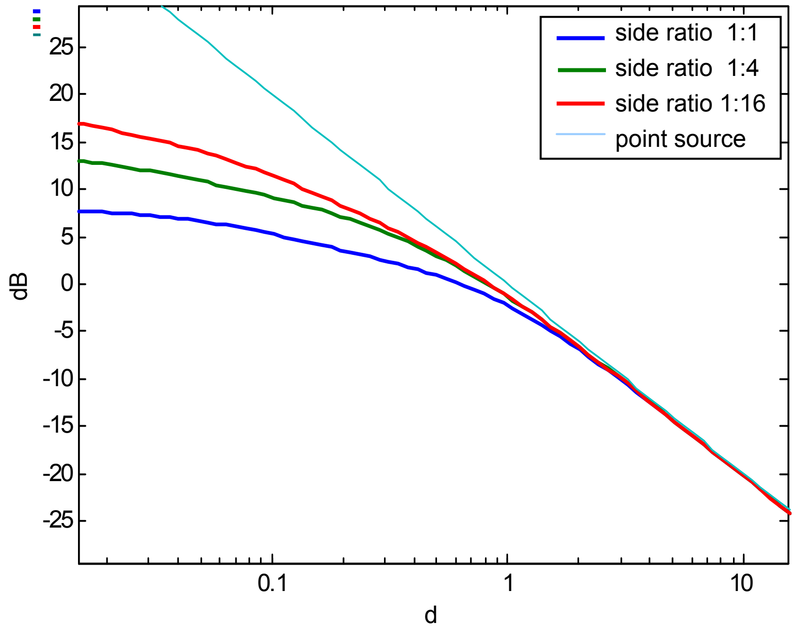

Fig. 2. Comparison of sound radiation of plate sources of various edge ratio to the radiation of a simple point source.

Obviously, all of these models take into account just the amount of radiated energy, without considering the direction of radiation whatsoever. In order to tackle the problem, Maekawa has also introduced a hypothetical radiation characteristics term cos(φ) without justification, which was further extended by Hohenwarter [7] but experimental validation of these models is very limited.

3 Numerical models

3.1 Structural finite element model

Numerical calculation of the noise radiated from mechanical structures is quite straightforward and even industrial routine nowadays, provided that a FE model for the structure can be developed and appropriate load information is available. Nevertheless, what may be true for relatively small, welded structures of the automotive industry, is not necessarily valid for buildings or other large-scale civil structures. Our experience has shown that the technique can be applied for relatively small rooms in buildings with solid concrete framework [8], but problems can arise – and the applicable frequency range can be very much limited – for welded and riveted steel structures too, if the dimensions are very large compared to the typical wavelengths of the bending waves in the structure (see the problem of a steel bridge in [9]).

3.2 Source simulation technique

The source simulation technique (SST) is based on the idea that any source can be substituted by a large number of spherical wave functions, i.e. by hypothetical point sources, put in the interior of the radiating body. These functions satisfy the Helmholtz radiation equation by definition. The number, place and source strength of the simulating point sources are defined such that the resulting sound field fulfils the boundary condition, prescribed for the surface of the vibrating body.

The technique, summarized e.g. by Ochmann in [10], is a fast numerical method which is often used for theoretical radiation and mainly scattering problems. On the other hand, very few industrial applications using SST have been published.

3.3 Energy equivalent point source model

The energy equivalent point source (EPSS) model is based on the assumption that any source can be substituted by a small number of incoherent monopoles, the total sound power of which is equal to the power radiation of the original source. In order to derive the volume velocities of the substituting monopoles, the source is surrounded by a hypothetical, closed surface, subdivided into partial surfaces which correspond to various parts of the radiating body. The sound power components propagating through the partial surfaces are measured, e.g. by means of sound intensity technique, and the volume velocities of the substituting monopoles are derived. The total sound field can then be calculated, by attributing the calculated volume velocities to some selected elements of the BE mesh.

The method was originally developed by Verheij and co-workers as an experimental approach, with special regard to the optimal development of engine encapsulations of heavy diesel engines [11]. Augusztinovicz et al. have adapted the technique for numerical simulation purposes [12] and applied for the enclosure problem with success, and some other practical applications have also been published [13]. Still, its use for practical problems is hampered by the necessity of making a cumbersome sound intensity test around the whole source which is impractical, if not impossible, for many industrial applications.

3.4 Statistical boundary element method

The statistical boundary element method (SBEM), first introduced and discussed in [11], extends the EPPS method and has originated as a special application of the inverse boundary element method. It is well suited for our current applications too, being apt to supply reasonably accurate results from very few experimental data on the vibration of the sound radiating sources.

As noted above, the numerical version of the EPSS method is based on given energies, radiated from very few (as a matter of fact, just one for each partial measuring surface) element of the BE mesh. Though correct from the energy point of view, it is obvious that the resulting sound field will necessarily be different from that of the original source to be substituted. Instead of using just a handful vibrating elements, one can also make the assumption that larger surfaces of the source behave similarly, the surface velocity of which can therefore be characterized by one single vibration amplitude or very simple velocity distribution.

It is demonstrated by the case study described in Section 4.2.2, that the surface vibrations at different points along real-life sources show strongly varying distribution, but are far from being totally independent. Assume now that the total radiation surface is divided into n partial surfaces, along which the surface vibration is considered to be constant. The characteristic velocity of these partial surfaces can be obtained from either direct vibration measurement or, if no direct vibration measurement is possible or feasible, from an iterative inverse calculation based on sound pressure measurements in close vicinity of the radiating surface. If the appropriate velocities of all the partial source elements are derived, the far-field sound pressure components for any arbitrary point can be obtained by a simple boundary element calculation. Since only the points of one single partial surface are assumed to vibrate coherently but different partial surface parts are thought to be independent, the sound pressure components originating from the various parts are to be summed on energy basis.

4 Radiation models for source decomposition of a heating plant

4.1 Description of the problem

A 150 MW heating plant, see Photo 1, has been built in Budapest app. 35 years ago when no stringent environmental noise limits were in force. In the meantime the requirements have considerably changed and a routine measurement, related to the planned extension of the plant, has revealed that the noise level exceeds the maximum allowed value by 17 dBA under full power conditions. The operator has initiated an investigation, aimed at identifying the relative rank of the potential partial noise sources and to develop guidelines for the effective noise control of the currently existing equipment.

Based on a few orientation measurements and thorough examination of the spot it was found that rather than just one single dominant source, most probably a number of various parts of the plant can play an important role in the noise emission. Therefore, a careful measurement series extended by model calculations was prepared and performed.

4.2 Experiments

The aim of the first set of measurements was to determine the sound power of all potential partial source, followed by calculation of their relative contribution to the critical immission points in the environment. One of the critical buildings was a 10-storey block of a housing estate at app. 160 m from the closest boiler/stack unit (later on: immission point #1); the other point was at the area just on the other side of a main road next to the boiler building (immission point #2).

The measurements were concentrated on one boiler unit, lying closest to the housing estate and operated nearly at rated power in the course of the whole measurement series. The near-field sound radiation of the following parts and elements were measured:

- outlet opening of the stack, by means of a special microphone holder fixed close to the outlet;
- sidewall of the stack, by using a microphone moved by a cord and pulley-wheels along the stack;
- sidewalls of the boiler in a large number of fixed microphone positions;
- inlet openings of the air blowers by fixed microphones;
- safety glass wall along the façade;
- transformer house
- gas station and its piping.

The immission point #1 was measured at night, but due to the traffic along the road next to the plant, no measurement was possible in point #2 at all.

In the second set of measurements surface vibrations along those partial sources were measured which had been found to be dominant sources for the environment: along the sidewalls of the boiler and the stack.

4.2.1 Results of the near-field sound measurements

The measurements have resulted in a large amount of data, out of which only a small subset can be depicted here. As an example, Fig. 3. summarizes the used noise and vibration measurement points selected along a vertical plane of the axis of the stack and the boiler, and Fig. 4. illustrates the corresponding noise levels. The highest pressure levels can be observed around the opening of the stack, suggesting that the opening has most probably strong influence on the noise emission, but does not necessarily constitute a dominant source too, the stack opening being of much smaller area than the sidewall of the stack. The results of other near-field noise measurements will be discussed in relation to their relative contribution to the critical immission point, see Section 4.3.

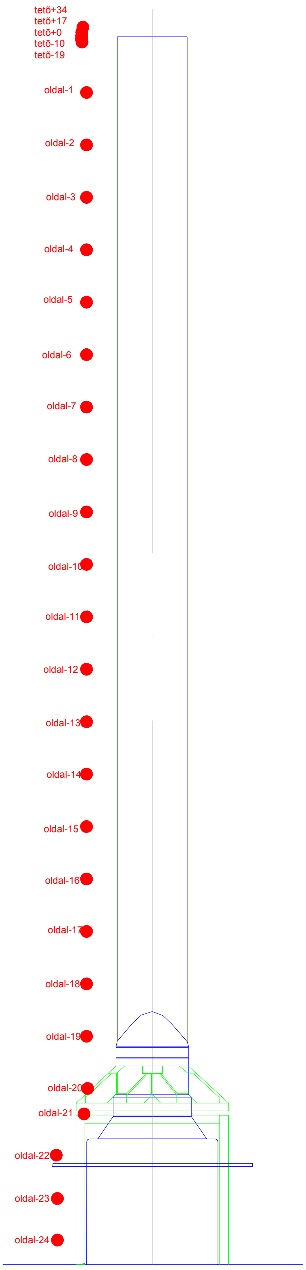

Fig. 3: Measuring points along the stack and the boiler

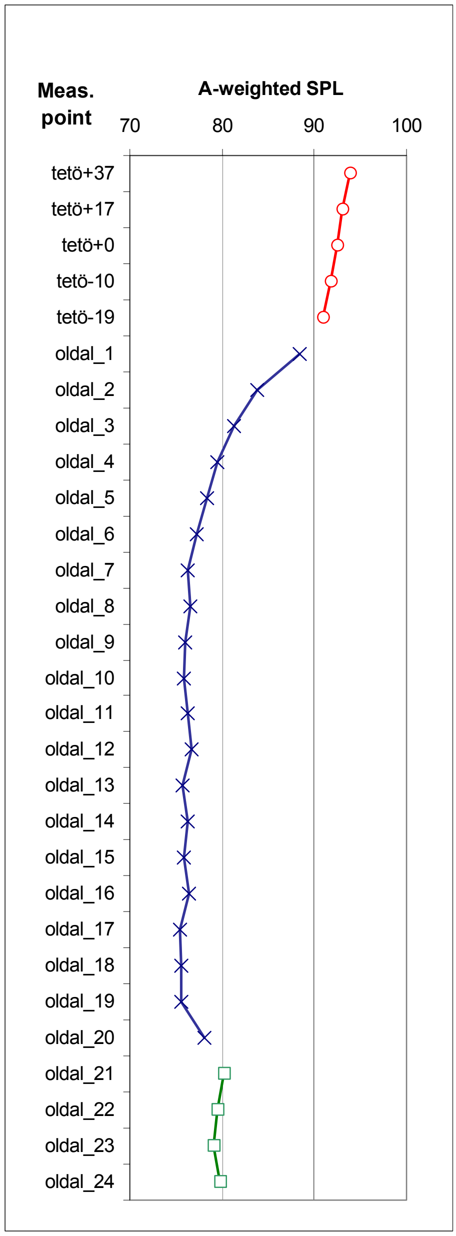

Fig. 4. Measured A-levels along the measuring points of Fig. 5.

4.2.2 Vibration and coherence analysis of surface vibrations

In order to get a better insight into the vibro-acoustic behaviour of the system under investigations, the vibration of the boiler and the stack was measured in a number of points, and narrow-band, third-octave band spectra and coherence functions were determined. Fig. 5. depicts the vibration measuring points used for coherence analyses, and Fig. 6. shows two sets of coherence measurements for the boiler and for the stack.

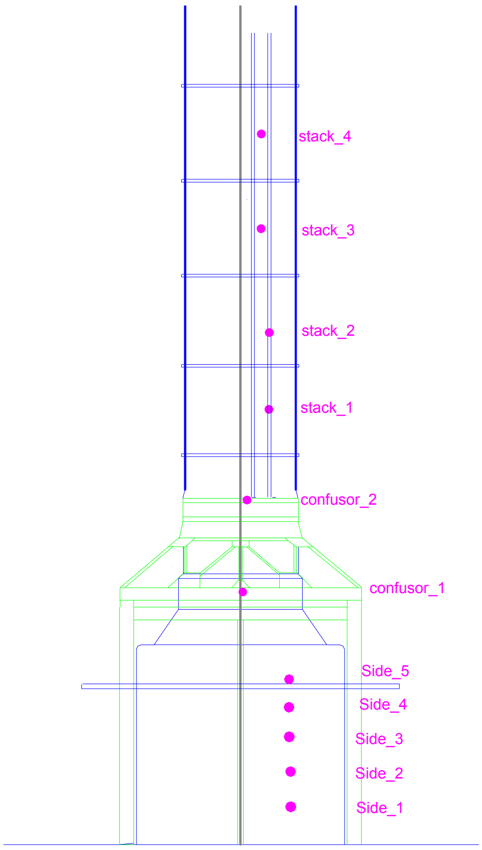

Fig. 5. Vibration measurement points along the boiler and the lower part of the stack, used for coherence investigations

The results are instructive, though not easy to interpret. Generally speaking, the vibration spectra consist of both random and periodic components for the boiler and the stack alike. The vibrations along the boiler seem to be more coherent, with clear maxima for frequencies where stronger periodic components are there in the vibration signal. On the contrary, the vibrations along the stack are more wide-band and still its surface vibrations are less coherent. One possible explanation is that the stack vibrations are determined by turbulent pressure variations inside the stack, while the boiler vibrations are generated by acoustic resonances of the boiler interior.

Even if one cannot draw general conclusions for the noise generation mechanisms from these analyses, some rough estimations on the size of the coherent partial sources can be made. Taking 50% coherence as an arbitrary limit value to distinguish between coherent and incoherent points, one can say that the coherence length along the boiler is about 2.5 m in vertical direction. (Note that the coherence length is considerably less in horizontal direction, which can be explained by the orthotropic cover material of the boiler.)

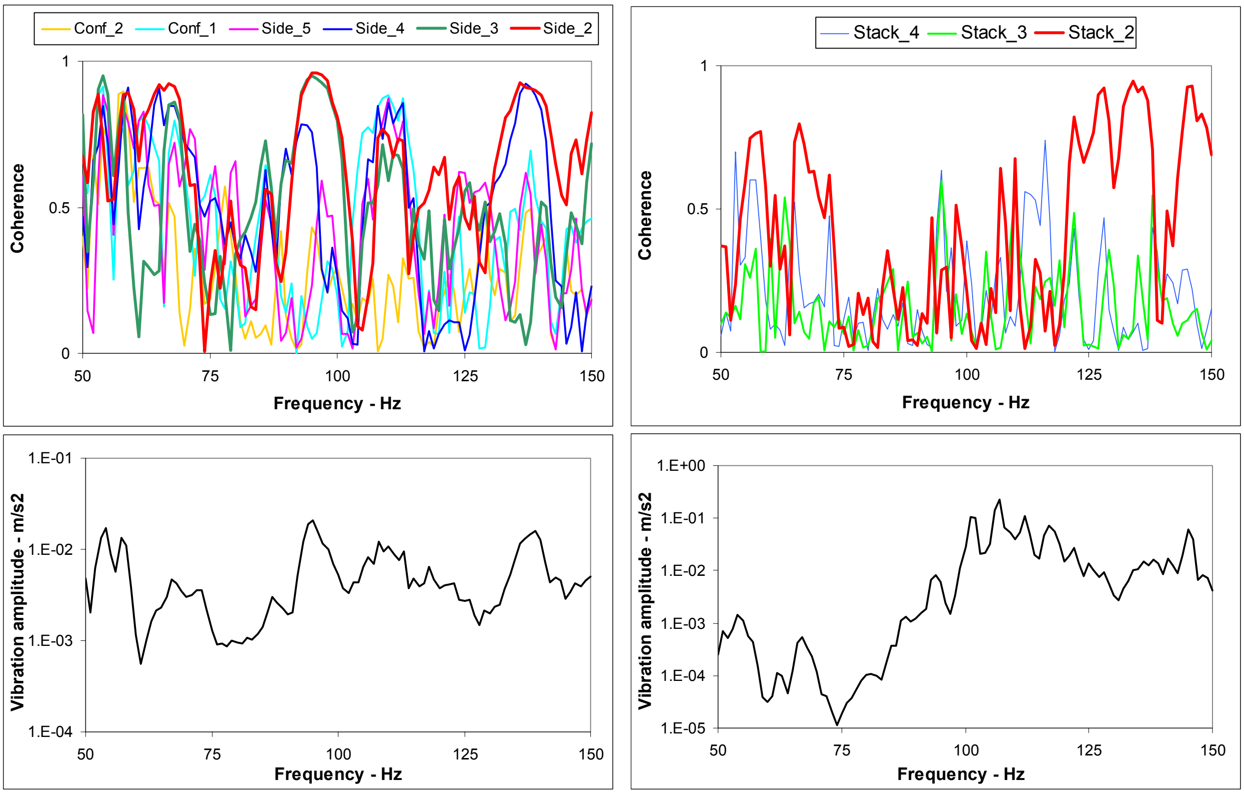

Fig.6a. Coherence functions, measured between various points of the boiler and the stack. (For the point notation see Fig.5.) **Left diagrams:** narrow-band spectrum of the reference point Side_1 and ordinary coherences for Side_2 to Side_5, Confusor_1 and Confusor_2, all referenced to Side_1. **Right diagrams:** narrow-band spectrum of the reference point Stack_1 and ordinary coherences for points Stack_2 to Stack_4 with respect to Stack_1

4.3 Source decomposition by means of analytical methods

The contribution of the potential partial sources has been calculated by determining their radiated power and calculating the far-field sound pressure from source models, corresponding to their geometry and relative position to the far-field. These latter calculations have been performed in different ways:

- on the basis of a Hungarian standard [17] which, in good agreement with the relevant ISO method [16], is based on a simple point source approximation according to Eq. (1b), and takes into account source characteristics and other transmission conditions by means of correction factors. This method will be denoted by "standard" method later on;
- on the basis of more sophisticated models according to Maekawa, Janeček and Hohenwarter.

The final results, expressed in terms of A-weighted sound pressure level spectra calculated for the far-field immission point #1, are summarized in Fig. 7, derived by the standard method. It is very clear that for low frequencies the dominant partial noise source is the stack opening, followed by the side wall of the stack and the boiler. The relative contribution of these sources is decreasing towards higher frequencies, where the gas station and the façade becomes more and more determinant. The agreement between the measured and calculated spectrum is quite good (with calculated total A-level 56.1 instead of measured level of 57.1 dBA), except for the 100, 125 and 200 Hz band. The 200 Hz component was found to be generated by the ventilation openings of a nearby transformer house, but it was not yet possible to identify the exact reason of the strong (as a matter of fact, even predominant) 125 Hz component. We presume that the deviation is caused by a strong narrow-band component in the airborne sound of the stack as measured at the opening, as well as temperature- and air movement dependent free-field propagation effects which are not taken into account in the propagation model properly.

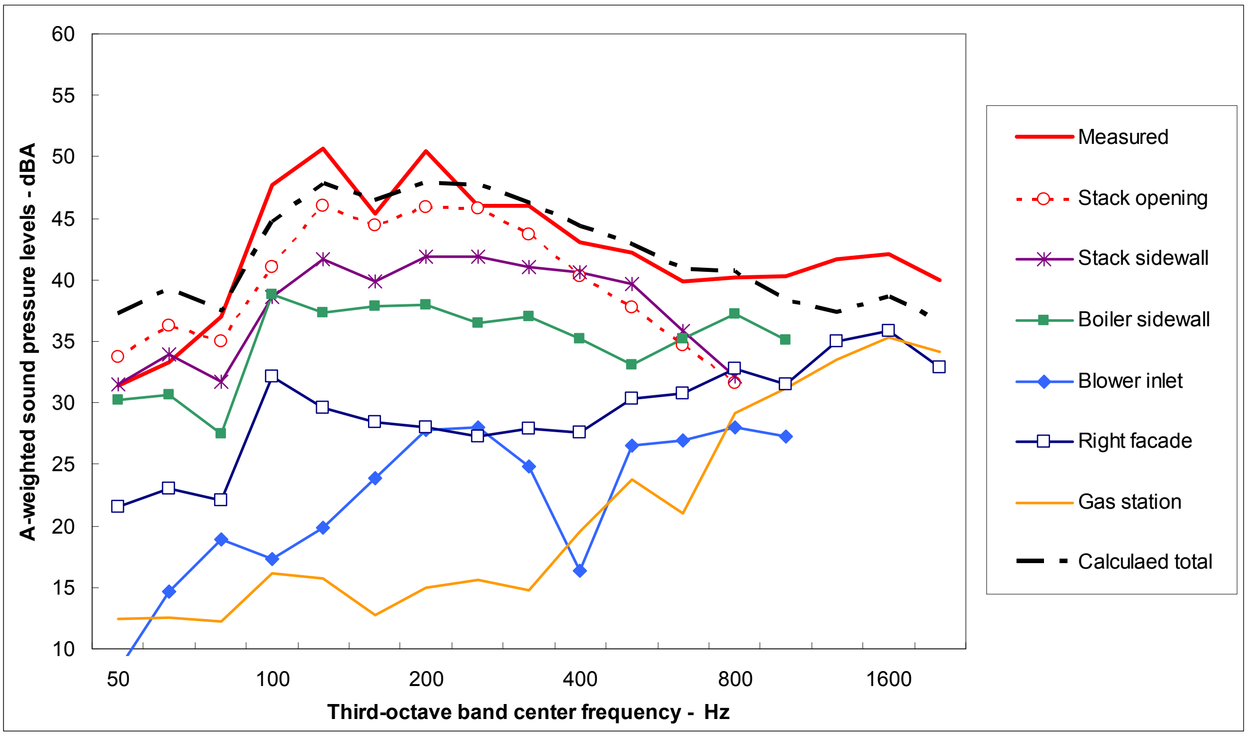

Fig. 7. Source decomposition of the far-field noise spectrum at the immission point. Thick, red line: measured total noise, black dash-dot line: calculated total noise. Other lines depict the contribution of the partial noise sources.

The calculations were also repeated by more detailed models discussed above, and no essential difference was observed. Recalling the theoretical considerations of Section 2.1 the explanation is not too difficult. At distances of more than multiples of the largest dimension, any source tends to behave as a point source, hence no improvement with respect to the simplest, i.e. point source, model can be achieved. Nevertheless, this is not the case for the immission point #2 which is much closer to the plant. This problem has been tackled by the BE method.

4.4 Radiation calculation by means of the statistical boundary element method

The boiler and the stack was modelled by a somewhat simplified boundary mesh, and on the basis of app. 25 vibration measurement points and the coherence measurements shown above, a boundary element model was developed. A typical velocity distribution is illustrated in Fig. 8. for 100 Hz. The appropriate partitioning of the mesh into independent pistons and the determination of their velocities were generated on the basis of direct measurements and their inter- or extrapolation.

The BE calculations were performed for a few selected points on the roof of the boiler building at distance of 7, 10.4, 15.6 and 25m (points A, B, C and D, respectively), which were used to validate the predictions for the immission point #2. The obtained results are summarized in Fig. 9., where four different data sets are compared: calculations by means of the standard method, Janeček's detailed model and statistical BEM are compared to direct measurements. All methods give similar results for the three lowest bands, but the statistical BE method performs better for 100 Hz. It is worth noting that this is one of the critical bands where significant deviation was found between the measured and calculated levels for immission point #1 as well. Therefore, results of these SBEM calculations are encouraging, even though further research to establish practical guidelines in relation to the optimal selection and scaling of the partial sources is still required.

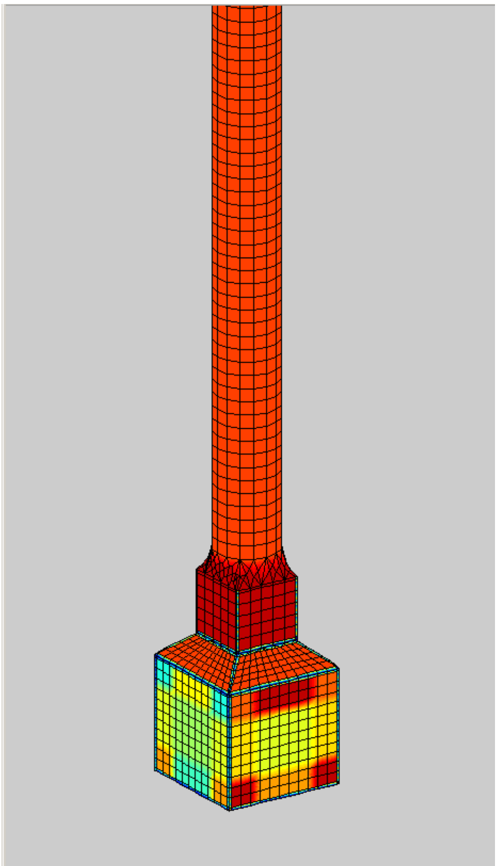

Fig. 8. BE mesh and velocity boundary conditions, used for the statistical BE calculations of the boiler/stack unit.

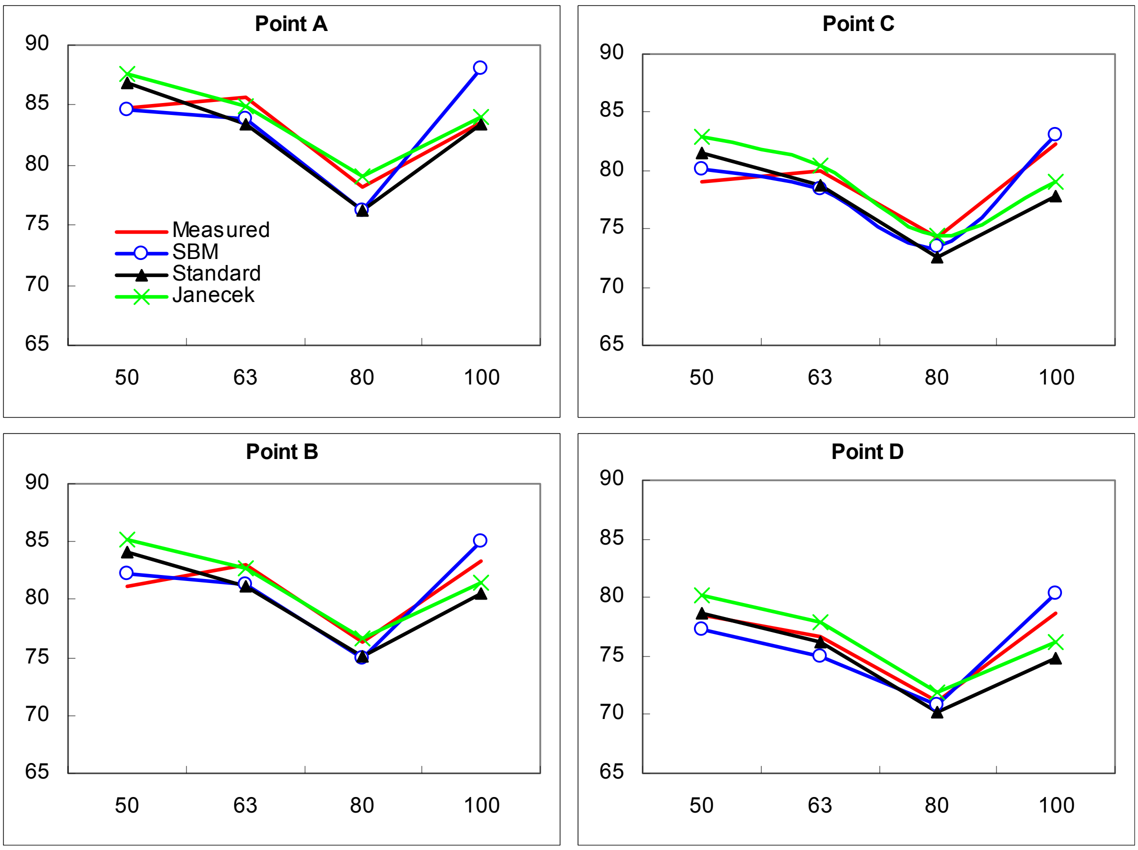

Fig. 9. Comparison of calculated and measured sound pressures for points A, B, C and D (see text).

5 Conclusions

The application of various analytical and numerical models for a complex industrial problem has revealed that the far-field noise radiation of the plant can be predicted with sufficient accuracy, not only in terms of A-weighted total sound pressure levels but as a function of third-octave band levels too, provided that the point of calculation is far enough from the source. The general rule of thumb, i.e. the immission point should be farther than a few multiple of the largest dimension of the source (in our case 160 against 42 m) was found to be justified. Nevertheless, the accuracy of analytical calculations for smaller distances is lower. Here the statistical boundary element method is still a viable option and its results are in better agreement with the measurements. The statistical BE method – as any other BE technique – is limited in frequency range and considerable computational effort is required but it can be used for a wide range of systems and equipment where other numerical technique fail or cannot be applied at all.

6 Acknowledgement

The authors would like to express their gratitude to Mr András Muntag for a number of valuable discussions on noise modelling of industrial plants, and to Mr Mátyás Farkas and Mr József Kóbor for their help in preparation of the extensive measurement series. Special thanks is also due to LMS International for their support of Laboratory of Vibroacoustics.

7 References

[1] *Directive 2002/49/EC of the European Parliament and of the Council of 25 June 2002 relating to the assessment and management of environmental noise* - Declaration by the Commission in the Conciliation Committee on the Directive relating to the assessment and management of environmental noise. Official Journal L 189 , 18/07/2002, p.12 – 26.

[2] See respective information on the website of the EU Project IMAGINE (**www.imagine-project.org**)

[3] Website of the EU Project HARMONOISE (**www.harmonoise.org**)

[4] Deliverable D2 of the IMAGINE project: “State of the art in noise mapping”. (www. imagine-project.org/bestanden/D2 state of the art (v31) + appendices.pdf)

[5] Z.Maekawa: “Noise reduction by distance from sources of various shapes”. *Applied Acoustics*, Vol. 3, pp. 225-238. (1970)

[6] P.Janeček: “A Rectangular Plane Sound Source”. *Applied Acoustics*, Vol. 27, pp. 263-274 (1989)

[7] D. Hohenwarter: “Noise Radiation of (Rectangular) Plane Sources”. *Applied Acoustics,* Vol. 33, pp. 45-62. (1981)

[8] A.B. Nagy, P. Fiala, F. Márki and F. Augusztinovicz: “Prediction of interior noise in buildings, generated by underground rail traffic”. Paper to be published at the *8th International Workshop on Railway Noise,* Buxton, 8-11 September 2004.

[9] F. Augusztinovicz, F. Márki, K. Gulyás, A.B. Nagy and P. Fiala: “Vibro-acoustic design of a tram track for a steel road bridge”. Paper to be published at the *33th International Congress and Exhibition on Noise Control,* Prague, 22-25 August 2004.

[10] Ochmann, M.: “Source simulation techniques for solving boundary element problems”. In: *Boundary elements in acoustics - Advances and applications* (Ed.: O. von Estorff), WIT Press, Southampton, Chapter 7 (2000)

[11] Verheij, J. Hoeberichts, A.N.J. and Thompson*,* D.J., “Acoustic source strength characterization for heavy road vehicle engines in connection with pass-by noise”. *Proc. 3rd Int. Congress on Air- and Structure-Borne Sound and Vibration*, (Ed. M.J. Crocker), Montreal, Vol. I, pp. 647-654 (1994).

[12] F.Augusztinovicz, P. Sas, L. Cremers, R. Liebregts, M. Mantovani and C. Bertolini, "Prediction of insertion loss of engine enclosures by indirect BEM calculations, combined with a substitution monopole source description technique". *Proc. 21st Int. Seminar on Modal Analysis* (Ed.: P. Sas), Vol. I. 55-68.p.

[13] Agahi, P., Singh, U.P. and Hetherington, O.J., Numerical simulation of noise scattering using equivalent power volume velocity method. CD Proc. *Inter-Noise 99*, Fort Lauderdale (1999)

[14] Márki F., Augusztinovicz F., "Statistical - inverse boundary element method." *CD Proc. 27th Int. Seminar on Modal Analysis,* Leuven (2002)

[15] VDI 2571: "Schallabstrahlung von Industriebauten". VDI-Richtlinie, Herausg.: Normenausschuss Akustik, Lärmminderung und Schwingungstechnik im DIN und VDI (NALS), 1976.

[16] ISO 9613-2:1996. *Acoustics -- Attenuation of sound during propagation outdoors -- Part 2: General method of calculation*

[17] MSz 15036:2002. Outdoor sound propagation (In Hungarian)

Photo 1. The testing object: 150 MW heating plant in the 14th district of Budapest

Photo 2. Mounting of the microphone for near-field measurement at the stack opening

Photo 3. Boiler, confusor and lowest part of the stack.