

Synthesis of noise from a fan-type source placed in a complex installation

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Within an EC Growth project GRD1-1999-10785 'Nabucco' a particular approach, the Noise Synthesis Technology (NST), has been developed. It concerns industrial products where noise is generated by individual sources – components – implanted into a passive main frame – housing. The originality of NST is that it predicts trends in the overall noise by combining data from real noise sources with a simplified modelling of the main frame using a modified sub-structuring technique. The simplified frame model has the advantage of being more robust and more easy to implement for the purpose of noise spectrum prediction and auralisation.

Noise sources which are incorporated into built-up assemblies, such as fans, compressors, motors, pumps etc, are clearly responsible for the noise of the assembly but are not the sole factor in the process of noise generation. Two additional significant factors play role in the final noise of the assembly: the way the noise source is implanted into the structure, comprising its orientation, structural and other coupling etc. the way the structure further modifies the noise input from the source before it reaches the listener's ear. Under the action of noise generating components the assembled structure often amplifies the overall noise. Typical examples of products which generate noise in this way are HVAC installations, household appliances, outdoor machinery, computation equipment etc. In these and similar products noise is transmitted to the surroundings as a direct air-borne noise, structure-borne noise (via feet, supports, etc) and frequently fluid-borne noise (via ducts, pipes, etc). The latter two noise mechanisms are rarely dealt with in industrial conditions.

Outline of NST technology approach

NST uses an evolution strategy for noise reduction. It builds on an existing generation of products with the aim of improving their noise performance. Some generic acoustic properties of the products belonging to the same class (e.g. home dishwashers) can be established from careful measurements or computation followed by some specific data processing. Once identified, these generic properties will be combined

with data from real components – noise sources – in a computer analysis which will predict overall noise created by the assembled product. This should help the designer to synthesise the future product in a noise sensitive way: thus the name Noise Synthesis Technology (NST).

The first fundamental concept of NST is that of a component – noise source – which generates noise through an interaction with its structural assembly. Here, a source is taken into account in a realistic rather than an abstract way, the latter being usually the case when the prediction is carried out by computation only. This is achieved by carefully extracting out of specific measurements the full noise information about the component – air-borne, structure-borne etc. Measurements cannot be standardised in a unique way but have to be adjusted to the requirements of NST technology. The noise data are subsequently compacted, bearing in mind the coupling effects. The result is a noise descriptor, the Component Source Strength (CSS) which characterises the source. One source will usually have several CSSs. Via the CSSs the noise source is described by a minimum – yet complete – set of independent noise descriptors. A descriptor is not necessarily noise directly emitted by the source, but some measurable quantity such as vibration of feet, responsible for noise generation.

Typically, a fan will have one or several CSSs describing its air-borne noise emission and a few CSSs which take care of structure borne noise.

The second fundamental concept of NST is that of a Generic Structural Model. A Generic Model is a synthetic structure, either physical or virtual, which represents in a simplified way

the frame of a real industrial product. The role of any Generic Model is to provide information on noise transfer from the component(s) either directly or via the connections and the frame structure to the listener's ear. In order to fulfill this role, a Generic Model has to have the same generic properties as the product it represents (e.g. a ventilation unit within a product range all incorporate a framework and panels of similar size, thickness, cross section etc.).

The Generic Model thus represents an artifact which unites dislike noise generating mechanisms (air-borne, structure-borne, fluid-borne) on a common basis and, in addition, provides quantified data on noise transfer from the source to the listener's ears. The frame would usually be too detail-sensitive to allow for any reliable deterministic handling. NST makes a compromise by treating the frame as a combination of stable vibroacoustic features, driven by basic design characteristics, and fuzzy (dispersed) ones emanating from structural details. Existence of uncertainties in the frame behaviour makes the final results attainable in statistical terms: via an expected value and its deviation probability. The noise transfer data within the noise synthesis procedure assume the form of Frame Conductivity Functions (FCFs). Each FCF represents a transfer function between an excitation exercised by one particular source mechanism (defined by its CSSs) and the sound at the listener's position due to this mechanism. If the noise due to some of generating mechanisms is transmitted via one or several connections, such as resilient mounts, the corresponding Connection Transfer Functions (CTFs) have to be inserted in between the CSSs and FCFs.

A GSM will be as a rule a material object. While such an object would be workshop made, in some cases the original structure itself could serve as a GSM, especially if the manufacture technology makes the production of a custom-built GSM impractical.

The baseline characteristic reveals generic properties of the structure analysed, unperturbed by small structural changes. The fuzzy characteristic reflects the fact that structural detail and even circumstances may affect vibroacoustic behaviour. It defines the dispersive features of the individualised response spectra: the envelope around the baseline, the resonance density and the damping. The baseline and fuzzy functions form a complementary generic data pair. This pair is the same for similar structures: as a matter of fact, structures are identified as being similar if their generic characteristics are comparable.

The identification of baseline and fuzzy characteristics is done by a) identifying usual response transfer functions and b) carrying out specific post-processing on these functions. As a rule, the step (a) will be done by measurements. Each FCF is obtained from raw transfer functions. FCFs are complex functions, containing amplitude and phase data. Once identified, the Component Source Strength and the Generic Model data are combined within a computer for carrying out the global noise prediction. The underlining integrating approach is the sub-structuring, [1-3]. The basics of NST computation is given in [4]. Unless the source impedance is substantially higher than the frame impedance, the frame excitation has to be computed using mobility matching rules applied to interfaces source - frame. This will produce excitation acting on the frame which can be radically different than that of the source taken in isolation (CSS).

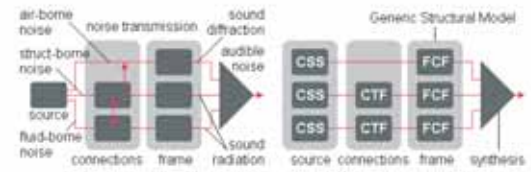


Fig. 1 : Noise Synthesis Technology: physical representation of noise generation (left) and its NST modelling equivalent (right)

A big advantage of NST is the realism in dealing with genuine, complex noise sources, such as fans. This is rarely done nowadays. In the other hand, use of a Generic Model for the representation of noise transmission will give predictions of a statistical rather than an exact nature, i.e. it will show tendencies rather than exact levels. But the statistical character of results is largely compensated here by an increased reliability which can rarely be attained when relying solely on computation methods. Finally, the completeness of NST approach permits, in the cases where fully applied, an audible reproduction of noise of the future product. This feature is meant to enable an assessment of sound quality of the product.

The originality of NST approach emanates from three complementary positions:

- as a technical methodology it combines advantages of two alternative types of techniques, experimental and computational, to produce a synergistic added value.
- as an industrially dedicated technology it creates a major breakthrough by uniting the efforts of main industrial parties: component manufacturers and product assemblers.
- as a noise control strategy it places a component – the noise source – and its integrating structure – the noise transmitter – in a concurrent position with the goal of synthesising, comprehending and improving the noise performance of the assembled product.

Principal steps of NST approach

One of the basic features of NST approach is its product-dependence, meaning that the general NST principles have to be tailored to each product. Nevertheless, there will be some common activities in each NST analysis. These can be grouped under three technical steps:

Frame analysis

- 1.1 Identify products having comparable generic features
- 1.2 Analyse frame characteristics from input data
- 1.3 Produce generic structural model of frame (GSM)
- 1.4 Verify that GSM has the same generic features as originals
- 1.5 Produce frame transmission characteristics - frame conductivities (FCF)
- 1.6 Adjust GSM until its response synthesised data match real GSM data

Component analysis

- 2.1 Select the appropriate technique of component characterisation

- 2.2 Characterise component(s): produce source data (CSS)
- 2.3 Characterise the links component-frame if applicable
- 2.4 Optimise CSS: reduce number of CSSs to essential minimum

Synthesis

- 3.1 Synthesis analysis 1: select optimum component(s) evaluate how different components affect assembly baseline (stable) response
- 3.2 Synthesis analysis 2: study component(s) Identify noise generating mechanism(s) and frequency(es) for noise reduction
- 3.3 Synthesis analysis 3: study frame and connections Evaluate impact of potential modifications on response noise spectra

Product Noise Synthesiser (PRONS)

PRONS is a software, developed by HEAD Acoustics, which should enable the operator – user of NST technology – to carry out all the essential technical steps of the noise synthesis. PRONS does not deal with the characterisation of either the component(s) or frame structure. This has to be done separately, outside PRONS. Once these characteristics are evaluated, PRONS takes over and does all the operations leading to noise synthesis.

Role of PRONS

- Select the least noisy component(s) relative to the given structure
- Rank different noise transmission paths
- Predict product noise
- Get an appreciation of product noise quality
- Assist in the analysis of noise reduction

Basic PRONS operations

- Configure NST model appropriate to the product analysed
- Carry out impedance matching of the component(s) to the structure
- Compute output noise spectrum from the supplied CSS and FCF data
- Enable blending and weighting of different noise path contributions
- Synthesise noise waveform from input data
- Check data format & consistency, enable data conversion

NST modelling applied to a fan

In order to adapt the real fan characteristics to the NST approach, a suitable fan model has to be defined and the measurement results taken on a particular fan fitted onto this model.

The classical literature treats the sound generated by the interaction of blades of a subsonic axial fan operating in an airflow as an acoustical dipole [5,6]. This model has been verified in ducted conditions [7]. Simplified models of different fans have been created which can be used in NST approach [8-12]. Some recent measurements show that the 1/3 octave band directivity of an axial fan, freely suspended in

an anechoic room, looks more like a monopole than a dipole [13]. A more detailed analysis of this case has revealed that the monopole component dominates at the blade passing frequency and some other isolated tones, while the dipole component dominates at other frequencies and is responsible for the non-coherent part of sound power. It was concluded that an axial or a mixed flow fan can be modelled by using a “modified dipole”, which treats blade passing frequency and shaft frequency differently from others. A centrifugal fan mounted inside a cavity is modelled as a monopole with the correction of the volume of the cavity. Both models work well in prediction by using NST.

The following outlines the synthesis procedure for fan-excited product assembly.

Matching source-structure

Air-borne CSS: The air-borne (AB) fan strength will be taken as unaffected by the structure. The sound at the observation position due to AB excitation where m AB transmission paths exist will be:

$$p_{AB} = \sum_m CSS_m^{AB} \Phi FCF_m^{AB} \tag{1}$$

CSSs of a fan will be given in terms of monopole and dipole strengths. One monopole and one dipole may suffice for the purpose, [13].

Structure-borne CSS: The fan will usually have several connection points and several degrees of freedom at each point, which imposes the use of matrix representation of governing equations. The coupling structure-borne (SB) forces and moments Φ at the contact positions are:

$$\{\Phi\} = -[M_e + M_r]^{-1} \{CSS^{SB}\} \tag{2}$$

CSS_{SB} – velocity vector of the source before coupling, M – mobility matrix, e & r – excitation, reception.

The coupling velocity vector reads:

$$\{v\} = M_r [M_e + M_r]^{-1} \{CSS^{SB}\} \tag{3}$$

The sound pressure radiated by the structure driven by several (s) SB excitations will be:

$$p_{SB} = \{FCF_{SB}\}^T \{v\} = \sum_s v_s FCF_s^{SB} = \sum_s \lambda_s CSS_s^{SB} FCF_s^{SB} \tag{4}$$

FCFSB - vector of structural response to SB excitation, T – transpose.

Structure-borne CSS –connecting component to structure via inserted fasteners or mounts: If the fan is linked to the structure indirectly, e.g. via resilient mounts or rigid connectors, the mobilities of these have to be taken into account. The coupling forces & moments at the excitation side e and reception side r:

$$\{\Phi_e\} = [H_e] \{CSS^{SB}\} \quad \{\Phi_r\} = [H_r] \{CSS^{SB}\} \tag{5}$$

The coupling velocities:

$$\{v_e\} = \{CSS\} + [M_r]\{\Phi_r\} \quad \{v_r\} = [M_r]\{\Phi_r\} \quad (6)$$

The system matrices H read:

$$\begin{aligned} [H_e] &= [T_e(M_e + D_e)^{-1}T_r - (M_r + D_r)]^{-1} \\ [H_r] &= [T_e - (M_e + D_e)T_r^{-1}(M_r + D_r)]^{-1} \end{aligned} \quad (7)$$

where D, T - direct & transfer mobilities of connections.

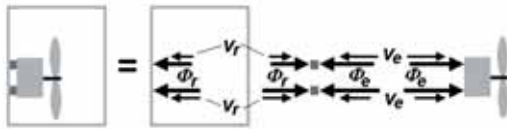


Fig. 2 : On the definition of vibratory variables in sub-structuring.

Sound pressure at the reception point

Sound pressure at the reception point results from excitations by all the sources :

$$p = p^{AB} + p^{SB} = \sum_m CSS_m^{AB} \Delta FCF_m^{AB} + \sum_s v_s \Delta FCF_s^{SB} \quad (8)$$

The mean square pressure thus reads (() - temporal mean value) :

$$\langle (p)^2 \rangle = \langle (p^{AB})^2 \rangle + \langle (p^{SB})^2 \rangle + 2 \langle p^{AB} p^{SB} \rangle \quad (9)$$

The first two terms represent the individual contribution of air-borne and structure-borne excitations. The third term represents the coupling contribution between these excitations. If the two excitation types are uncorrelated, the coupling term vanishes !

Conversion of the above to frequency domain yields pressure mean square spectrum. Each of three terms in (9) is a double sum over different CSS/FCF pairs :

$$\langle p^\alpha(t)p^\beta(t) \rangle \Rightarrow S_{p^\alpha p^\beta}(\omega) \quad S_{p^\alpha p^\beta} = \Re \left\{ \sum_\mu \sum_\eta \Lambda_{\mu\eta}^{\alpha\beta} H_{\mu\eta}^{\alpha\beta} S_{CSS_\mu CSS_\eta} \right\} \quad (10)$$

where α, β stand for any of two source types, AB or SB as appropriate, \Re - real part, * - complex conjugate, μ & η - indices referring to α and β respectively. Each spectrum given by (10) is a product of three factors: Λ , H and S.

The S terms in the sum (10) are the cross spectra between different CSSs of the α - β interaction. This function should be obtained by measurements on the operating source either fully disconnected from the reception structure or attached to a reference load. For uncorrelated sources $\Rightarrow S_{CSS,CSS} = 0$.

The Λ factor is a non-dimensional frequency-dependent complex function, which is a product between coupling strengths of α - β pairs :

$$\Lambda_{\mu\eta}^{\alpha\beta} = (\lambda_\mu^\alpha)^* \lambda_\eta^\beta \quad (11)$$

The H factor relates to the FCFs of α - β pairs :

$$H_{\mu\eta}^{\alpha\beta} = (FCF_\mu^\alpha)^* FCF_\eta^\beta \quad (12)$$

The major contribution to the sound pressure at the receiving points will normally come from first two square terms :

$$\langle (p^{AB})^2 \rangle + \langle (p^{SB})^2 \rangle$$

The double sum in the spectral representation of each of these can be split into 2 parts: a direct and a cross term :

$$S_{p^\alpha p^\alpha} = \sum_\mu |\lambda_\mu^\alpha|^2 |FCF_\mu^\alpha|^2 S_{CSS_\mu CSS_\mu} + 2 \Re \left\{ \sum_{\mu=2}^{\infty} \sum_{\eta=1}^{\mu-1} \Lambda_{\mu\eta}^{\alpha\alpha} H_{\mu\eta}^{\alpha\alpha} S_{CSS_\mu CSS_\eta} \right\} \quad (13)$$

All the summation members in the direct term, given by a single sum, are positive. This term will thus provide the main contribution to the pressure square. It represents the sound pressure which would have been created if the different excitations within the corresponding noise mechanism, AB or SB, were uncorrelated. The members in the cross term can be of either positive or negative sign, which will lead to partial cancellation of their contributions to the pressure square. The same applies to the mixed products originating from different noise mechanisms.

The noise spectrum at the reception position will be in a general case thus composed of three contributions, each of which is itself a sum of different noise paths: 2 by individual excitation mechanisms, AB and SB, and one by coupling of different excitation mechanisms. The contribution by each individual mechanism will be often dominated by excitations taken separately, partially due to decoupling of excitations and partially due to mismatch of different FCFs. Thus simplifications in the overall procedure will be possible.

Conclusions

NST technology serves for improvement of noise performance of industrial products composed of one or several noise sources (components) incorporated into a main frame.

Any application of NST to a particular industrial case requires specific data on the component(s) – CSS, and specific data on the frame structure – FCF. CSS and FCF are complex, frequency dependent functions. CSSs are specified in a unique deterministic way, while FCFs are given in terms of averaged values: baseline, supplemented by the dispersion – fuzz. A fan will typically have two air-borne CSSs and several structure-borne CSSs.

CSS and FCF data serve as input to noise prediction and synthesis which is done by a specialised software - PRONS. Prediction of

output RMS noise spectrum of the assembled product is done by PRONS via classical sub-structuring techniques. Very often different mechanisms will be uncorrelated while the effect of interaction between different excitations on resulting noise will be negligible in comparison to the direct contribution of these excitation, all of which will simplify PRONS analysis.

Acknowledgement

This work has been supported by the Commission of European Community within the project GRD1-1999-10785 'Nabucco'.

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