CHARACTERIZATION OF SOURCES OF STRUCTURE-BORNE SOUND

Björn A. T. Petersson

Institut für Technische Akustik, Technische Universität Berlin; Email: b.a.t.petersson@tu-berlin.de

Introduction

Sources of structure-borne sound receive increased consideration by researchers. This is in response to calls for practical ways to characterize them, which will yield data and methods useful for noise and vibration control and low noise product design. These calls come from manufacturers of components, which are sources of vibration and noise in assembled products, from designers requiring prediction methods in low-noise product development and from authors of standards on noise from installed products. Although much work has been put in, it is still the case that there is a lack of progress towards an approach for structure-borne source characterization, when compared with air-borne and liquid-borne sources [1-4]. A few prominent reasons are. A source characterization requires consideration of the active processes that are the origins of the vibrations. Additionally is required the structural dynamic characteristics of the source. For built-up units, moreover, involving several sources, the vibration transmission process is complicated and its full description requires large data set. The vibration of structures is sensitive to small variations in geometry, material and location of the excitation and response, and there are large variances in the ensemble of similar structures.

A practical source characterization ideally should be a quantity indicative of source strength and involve source factors only. The data set should be reducible, to simplify representation whilst highlighting the important transmission components and paths for control. At the same time, it should be in a form appropriate for combining with receiver factors in predicting transmission in the installed condition.

Source mechanisms and source units

For most noise and vibration problems, there is a complex interplay between mechanical, electrical, magnetic or thermal processes at the origin. Such processes or mechanisms can be singly responsible or be internal to a unit e.g., a machine, collectively responsible for the perceived stimuli. It is hence not obvious what is to be understood by the concept of source characterization.

In some cases it is possible to isolate and treat such a process directly e.g., the rolling process but in most cases one is forced to approach the problem as manifested at some remote interface e.g., at a machine footing. Examples of the first category – the source mechanisms – are impacts, friction, unbalances, magnetostriction and parametric excitation [5-10]. This is an important area of research since the dependences and interdependences of such source mechanisms set the scene for both applications and the possibilities to handle the second category – the source unit or source for short. Above all, it is the degree of non-linearity and the spatial (structural) invariance of the source mechanisms that give the frames for a source characterization. In the light of the raised practical interest mentioned in the introduction, however, the scientific beauty of the source mechanisms is herein resisted and the focus is put on the characterization of a source unit.

Idealized sources

The collectively imparted vibrations by different source mechanisms in a machine also manifest themselves at the contacts to the environment; in this case the receiving structure. This can be considered as a map of the internal activity when the machine is free from all connections. A measure of this activity – commonly described by the 'free velocity' v_{sf} – is not sufficient for a source characterization. This is readily seen from an expression of the complex power transmitted from the source to the receiver in an installed condition,

$$Q = \left|v_{sf}\right|^2 Y_R \Big/ 2\left|Y_S + Y_R\right|^2, \tag{1}$$

which demonstrates that also the dynamic characteristics of the source are involved – commonly expressed as its mobility Y_S. In this simple expression, valid for an academic machine undergoing unidirectional motion, Y_R denotes the receiver mobility at the single contact point. It can thus be concluded that a rigorous source characterization must comprise both these properties of the source. The reason for employing the complex power as the starting point for the source unit characterization is that both the farfield and the nearfield response of the receiving structure can be obtained from this quantity such that the two principal classes of applications, strength of materials/reliability and noise and vibrations, are encompassed simultaneously. By manipulating Eq. (1), it can be decomposed into two parts

$$Q = \frac{1}{2}\frac{\left|v_{sf}\right|^2}{Y_S^{\,*}}\frac{Y_R Y_S^{\,*}}{\left|Y_S + Y_R\right|^2} = SC_f, \tag{2}$$

the first of which solely consists of source related quantities whilst the second describes the coupling between the passive source and receiver structures. The first is termed the source descriptor and the second is called the coupling function [11].

Sources in practice

Although the academic case is instructive for principle analyses, practice is seldom so neat. Rather, the machines are usually connected to the receiver at several finite areas, which can be treated as points when small in comparison with the governing wavelength. Furthermore, there are in a general case six components of excitation and motion at each point, which also interact structurally. This means that the complex power for such a real installation is given by the matrix equation

$$Q = \frac{1}{2}\mathbf{v}_{sf}^{\;T}\mathbf{Y}_R^{\;T}\left(\mathbf{Y}_S^{\;H} + \mathbf{Y}_R^{\;H}\right)^{-1}\left(\mathbf{Y}_S + \mathbf{Y}_R\right)^{-1}\mathbf{v}_{sf}^{\;*}. \tag{3}$$

Apart from the extensive work implied in computing or measuring the mobility elements, the matrix formulation literally removes the transparency making it virtually impossible to assess possibilities for simplifications and data reduction. Most importantly, however, there is no straightforward way to generalize the decomposition of Eq. (2).

Three lines of developments

In order to remedy the situation, the concept of effective mobility can be introduced [12]. The effective mobility is defined as

$$Y_{ii}^{nn\Sigma} = Y_{ii}^{nn} + \sum_{\substack{j=1 \\ j\neq i}}^{6} Y_{ij}^{nn}\frac{F_j^n}{F_i^n} + \sum_{\substack{k=1 \\ k\neq n}}^{N} Y_{ii}^{nk}\frac{F_i^k}{F_i^n} + \sum_{\substack{k=1 \\ k\neq n}}^{N}\sum_{\substack{j=1 \\ j\neq i}}^{6} Y_{ij}^{nk}\frac{F_j^k}{F_i^n}, \quad (4)$$

which is the ratio of the actual velocity at a point and one component, due to the contributions from all excitations at all points, to the excitation component at the point considered. The symbol F must here be seen in a generalized sense such that force and moments are encompassed. By employing this concept in Eq. (2), the source descriptor becomes

$$S = \left|v_{sf}\right|^2 \Big/ 2Y_{ii}^{nn\Sigma^*}. \quad (5)$$

Owing to the interaction between points and components, this is no longer a quantity solely dependent on source factors, as is seen from Eq. (4), since a distribution of forces is implied. This force distribution has attracted much interest in recent years [12-14] and it is seen that for various combinations of built-up, generic structures, the ratio oscillates around a generally frequency dependent asymptote at frequencies above the first well separated eigen-frequencies. With such asymptotes introduced in (4), a physical source is subdivided into theoretical component sources, subsequently superimposed to meet the accuracy required.

Another line of development draws upon the observation that the mobility function has three distinct regions as indicated in Figure 1.

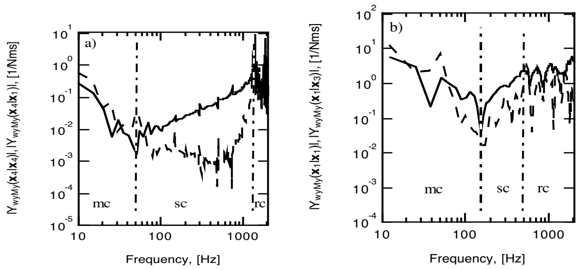

Figure 1. Examples of magnitude of point and transfer moment mobility for a compact (a) and a built-up (b) source.

The first region is mass-controlled (mc), the second is controlled by some stiffness (sc) and in the third the source is essentially controlled by resonances and anti-resonances (rc) [15]. Although the bandwidth of the regions vary for different source types, it is clear that the dynamic behaviour within a region remains the same for point, transfer and cross-mobilities. This means that a physical source can be interpreted as three theoretical sources, each of which having well defined dynamic characteristics. The mass-controlled mobilities are simply obtained from knowledge of mass and co-ordinates for centre of gravity, excitation and response points. In the stiffness- as well as resonance-controlled regions the mobilities can be estimated as skeleton mobilities for various structural designs [16].

The third and most recent addition considers the contact points as a single continuous interface. With this interface, forming a closed contour $C(s)$, field variables and mobilities can be series expanded, for example, by means of a spatial Fourier decomposition e.g.,

$$Y_{pq} = \frac{1}{C^2}\oint_C\oint_C Y(s \mid s_0)e^{-ik_p s}e^{-ik_q s_0}\,ds\,ds_0. \quad (6)$$

By means such defined 'interface mobilities' [17], the problem is formally brought back to the single point, single component formalism and the source descriptor follows from Eq. (5) with the effective mobility substituted by a sequence of interface mobilities. As indicated in Eq. (6), strictly both terms of equal order ($p=q$) and cross-order ($p\neq q$) exist. Asymptotically, the latter vanish and only terms of equal order remain. It is thus interesting from a practical point of view to relax the definition of the interface mobilities by only retaining Y_{pp}, see Figure 2. Upon employing this relaxed definition, it has been demonstrated for practical sources that only a few orders are required to give acceptable results [18].

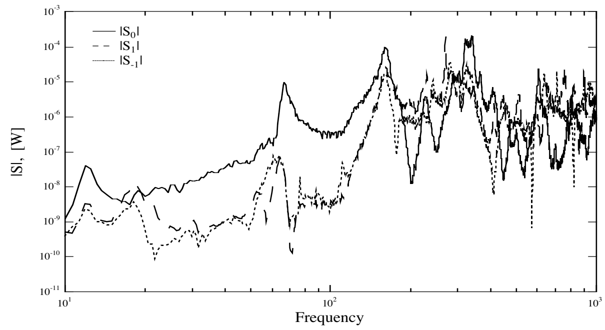

Figure 2. Three source descriptor orders

Concluding remarks

The overview given attempts to highlight the basis for characterization of sources of structure-borne sound. This is done by distinguishing source mechanisms and source units and to point at some of the inherent conditions for a physically correct characterization of source units. In that light, three conceivable lines of development are sketched, which all have that in common that the physical source is decomposed, either in source components as in conjunction with the introduction of the effective mobility or in elemental sources with well defined structural dynamic behaviour or in series expanded source orders. It can be concluded that all require some approximations in order to be attractive in engineering practice but are rigorously founded theoretically, observing the conclusion that source characterization necessitates the inclusion of both the activity and the dynamic characteristics of the source structure.

[1] Bodén, H., 9th Intl Cong. on Sound and Vibration, 1-30,2002.
[2] Gibbs B., Petersson, B.A.T., Proceedings IOA, 17(A), 139-147,1995.
[3] ten Wolde T., Gadefelt G.R., Noise Control Engineering Journal, 28, 5-14,1987. Note Errata in 28, 84,1987.
[4] Jones, A.D., Noise Control Engineering, 23, 12-31,1984.
[5] Koss L.L., Alfredson R.J., Journ of Sound and Vibr, 27, 59-75,1973.
[6] Kropp W., Applied Acoustics, 26, 181-,1989.
[7] McIntyre ME, Schumacher RT, Woodhouse J., JASA,74, 1325-1345,1983.
[8] Heckl M.A., Abrahams I.D., Journ of Sound and Vibr, 229, 669-693,2000.
[9] Petersson B.A.T., Building Acoustics, 2, 585-623, 1995.
[10] Cremer L, Heckl M., Körperschall, Springer Verl., 2. Aufl., Kap. 4, 1995.
[11] Mondot J-M., Petersson B. Journ of Sound and Vibr, 114, 507-518, 1987.
[12] Petersson B., Plunt J., Journ of Sound and Vibr, 82, 517-530,1982.
[13] Mondot J-M., Chalmers Univ. of Techn.,Dept Build. Acoust.,Report F86-04, 1986.
[14] Fulford, R.A., Gibbs, B.M., Journ of Sound and Vibr, 225, 239-282, 1997.
[15] Petersson B.A.T., Gibbs B.M., Journ of Sound and Vibr, 168, 157-176, 1993.
[16] Petersson B., Plunt J., Journ of Sound and Vibr, 82, 531-540,1982.
[17] Petersson B.A.T., Journ of Sound and Vibr, 202, 511-537,1997.
[18] Petersson B.A.T., Moorhouse A., Proc. 17th ICA (CD) Vol.1, 2001.