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MODELLING OF AN INDUSTRIAL MACHINE USING S.E.A.

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1. INTRODUCTION

A vibroacoustic model of an industrial machine is built in order to analyse its noise radiation. The geometrical and mechanical characteristics of the machine are complex. Its radiation spectrum is broadband. The application of discretization harmonic methods to our machine would require prohibitive amounts of data and would consume a huge computer time. These methods therefore appear to be unadequate for the purpose. Although rougher, energetic methods seem to be more suitable. AUTOSEA [1] is a software based on the principles of Statistical Energy Analysis. Using it, an S.E.A. model of the machine is built. In a first stage, the machine is split into subsystems. Its damping and coupling loss factors are measured using the power injection method. In a second stage, the main design characteristics of the machine are provided to the software. One obtains a model that is tuned according to measured values. Sound power level computed by that model approaches the real level of the machine with an average error around one to two decibels. The model allows fast parametric studies from which some possible noise reduction measures can be ranked in terms of efficiency.

2. SUBSTRUCTURATION OF THE MACHINE

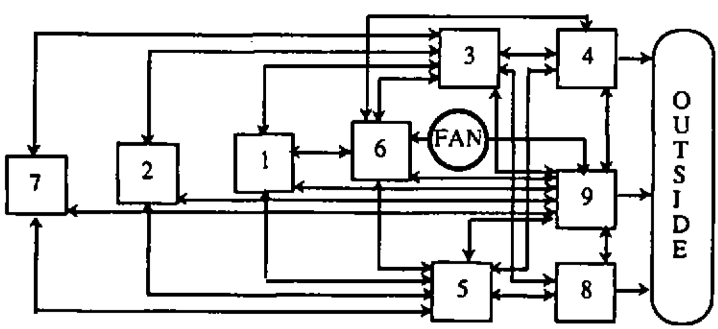

Figure 1 : Substructuration of the machine - Connections - Radiation to the outside
Power injection by the fan

The machine has a box like shape, its main dimensions being 1.2, 0.3 and 0.2 meters. It includes interconnected homogeneous, 1 mm thick, steel plates, most of them being plane ones. Connections between plates are made of screws or rivets. The only significant vibroacoustic source of the machine is a fan, which is installed in an inner cavity of the machine. The cavity communicates with the outside of the machine through a rectangular aperture.

MODELLING OF AN INDUSTRIAL MACHINE USING S.E.A.

According to S.E.A. principles, the machine is first idealized by splitting it into nine subsystems, the first eight ones being structures and the ninth one a cavity. The S.E.A. study is led in third-octave bands in the range [200 - 2500 Hz]. Frequency dependent quantities in this paper are therefore implicitly meant as third-octave band averaged ones. For simplicity, their frequency dependency is not mentioned in the equations. Figure 1 describes the substructuration of the machine and the connections between the subsystems. The fan injects power acoustically into the cavity and mechanically into its support, subsystem 6.

3. MEASUREMENT OF DAMPING AND COUPLING LOSS FACTORS

The power injection method [2] is used to derive damping and coupling loss factors. This method is applied by injecting a known power into one subsystem and simultaneously measuring the energy of all the subsystems. Owing to the machine compactness however, measurements are not performed simultaneously on the nine subsystems. Exact power balance required by the power injection method can therefore not be exploited. It is nevertheless approximated by two separate power balances : one on the system composed of the eight structures and one on the cavity.

3.1. Damping loss factors

3.1.1. Structural damping loss factors

Theory :

Let us first consider the system composed of the eight structural subsystems of the machine. In the third-octave band centered on frequency f_o, the following matrix equation can be written for that system :

$$\omega_o \; [\,E\,]_N^N \; [\,\eta\,]_1^N = [\,P\,]_1^N \qquad (1)$$

Where ω_o, the pulsation is equal to $2\pi f_o$, N is the number of subsystems (N=8) and $[\,P\,]_1^N$ is a vector whose general term P_i is the power input into subsystem i. $[\,E\,]_N^N$ is an N by N matrix whose general term E_{ij} denotes the energy of subsystem j when power P_i is introduced into subsystem i, no other subsystem than i being excited. $[\,\eta\,]_1^N$ is a vector whose general term η_i is the damping loss factor of subsystem i.
Connections being supposed non dissipative, equation (1) expresses the global energy balance of the system. It means that the whole power introduced into the system is dissipated by the damping. Structural damping loss factors are derived by solving (1).

Practice :

N experiments are necessary to elaborate linear system (1). Experiment i provides power P_i and the N energies E_{ij}. It consists of M excitations of subsystem i with one shaker, equipped with an impedance transducer. The point e of application of the shaker is different for each excitation.

P_i is computed as :

$$P_i = \frac{1}{M} \sum_{e=1}^{M} G_{ie}^{FF} \mathrm{Re}\,[H_{ie}^{VF}] \tag{2}$$

Where G_{ie}^{FF} and $\mathrm{Re}\,[H_{ie}^{VF}]$ respectively denote, for excitation e of subsystem i, the autospectrum of the force and, the real part of the transfert function between the velocity and the force at the point of excitation.
During excitation e of subsystem i, the velocity is measured on subsystem j ($1 \leq j \leq N$) at Q points. E_{ij} is computed as :

$$E_{ij} = m_j \left[\frac{1}{M} \sum_{e=1}^{M} \left[G_{ie}^{FF} \frac{1}{Q} \sum_{k=1}^{Q} \left| H_{ijek}^{VF} \right|^2 \right] \right] \tag{3}$$

Where m_j denotes the mass of subsystem j, and H_{ijek}^{VF} denotes, for excitation e of subsystem i, the transfert function between the velocity at measurement point k ($1 \leq k \leq Q$) of subsystem j and the force at the point of excitation.

3.1.2. Cavity damping loss factor

Theory :

Equation (1) is now applied to the cavity. In this case, (1) takes the following scalar form :

$$\omega_o E_{99} \eta_9 = P_9 \tag{4}$$

Where η_9 is the cavity damping loss factor, E_{99} its energy and P_9, acoustic power injected in it.

Practice :

Power P_9 is determined by substitution, using a loudspeaker. For input voltage U_o, power radiated by that loudspeaker is measured in an anechoic room. In the cavity, the fan is then replaced by the loudspeaker that is mounted in order to avoid any structural coupling with the machine. Input voltage being again tuned to U_o, it is supposed that the loudspeaker delivers into the cavity the same power as the one measured for the same voltage under anechoic conditions. P_9 being known, the spatial average p_9^2 of the quadratic acoustic pressure is measured in the cavity. E_{99} is then computed as :

$$E_{99} = \frac{V}{\rho c^2} p_9^2 \tag{5}$$

Where V denotes the volume of the cavity, c is the speed of sound and ρ denotes the mass density of the fluid. P_9 and E_{99} being known, η_9 can be derived from (4).

3.2. Coupling loss factors

The configuration of the machine makes it uneasy to measure the coupling loss factors between the cavity and the related structures. AUTOSEA is therefore used to generate theoretical values for these lacking data. Let us consider the coupling loss factors of the eight structure system.

Theory :

According to S.E.A., another way than equation (1) for expressing the energy balance of that system is the matrix expression (6) :

$$\omega_o \; [\,\Gamma\,]_N^N \; [\,E\,]_1^N = [\,P\,]_1^N \tag{6}$$

$[\,E\,]_1^N$ is a vector whose general term E_i denotes the total energy of subsystem i. $[\,\Gamma\,]_N^N$ is an N by N matrix whose general term is defined by :

$$\Gamma_{ij} \underset{i \neq j}{=} -\eta_{ji} \text{ and } \Gamma_{ii} = \eta_i + \sum_{\substack{i=1 \\ i \neq j}}^{N} \eta_{ij}.$$

Where η_{ij} is the coupling loss factor between subsystems i and j.
An important result of [3] is that equation (6) can be rearranged to determine coupling loss factors η_{ij}, independently of damping loss factors η_i. This result is briefly reminded hereafter.
Let N(i) be the number of subsystems physically connected to subsystem i. We want to determine the N(i) coupling loss factors associated to subsystem i. Let us introduce the set L, whose elements noted L (k) ($1 \leq k \leq N(i)$), are the *numbers* of the N(i) subsystems. Note that to simplify notations, L is not subscripted with i, although the content of L depends on i.
Let $\left[\bar{\eta}\right]_1^{N(i)}$ be the vector composed of the desired N(i) coupling loss factors of subsystem i. The general term of vector $\left[\bar{\eta}\right]_1^{N(i)}$ being defined as $\bar{\eta}_k = \eta_{L(k)\,i}$, the coupling loss factor between subsystem L(k) and subsystem i, then one can show that vector $\left[\bar{\eta}\right]_1^{N(i)}$ is derived using the following relation.

$$\left[\bar{\eta}\right]_1^{N(i)} = \frac{P_i}{\omega_o \, E_{ii}} \left\{\left[\bar{E}\right]_{N(i)}^{N(i)}\right\}^{-1} \left[1\right]_1^{N(i)} \tag{7}$$

Where $\left[1\right]_1^{N(i)}$ is the unit vector and the general term $\bar{E}_{km}$ of matrix $\left[\bar{E}\right]_{N(i)}^{N(i)}$ is defined as the following combination of the E_{ij} :

$$\bar{E}_{km} = \frac{E_{L(k)\,L(m)}}{E_{L(k)\,i}} - \frac{E_{i\,L(m)}}{E_{i\,i}} \tag{8}$$

MODELLING OF AN INDUSTRIAL MACHINE USING S.E.A.

The meaning of $E_{L(k)L(m)}$, $E_{L(k)i}$, $E_{iL(m)}$ and E_{ii} in the right hand side of (8) has already been defined. For illustration, $E_{L(k)L(m)}$ denotes the energy of subsystem L(m) when power $P_{L(k)}$ is introduced into subsystem L(k), no other subsystem than L(k) being excited. Formula (7) provides all the coupling loss factors associated to subsystem i. In order to get all the coupling loss factor of the model, it must therefore be applied N times.

Practice :

The method of power injection has already been applied to the eight structure system in order to get its damping loss factors. It has provided us with all the values of P_i and of E_{ij} that are required for determining the coupling loss factors. Neither extra data nor extra experiment is therefore needed in practice.

4. MEASUREMENT OF POWER INJECTED BY THE FAN

4.1. Alternative method to in situ measurement

In order to complete the input data of our model, the value of power injected into the machine by the fan is still needed. Fan injects power both acoustically into the cavity and mechanically into the fan support. Owing to the machine compactness, power injected cannot be measured in situ so that an alternative method is used. The fan and its support are removed from the machine. They are attached to a standardized plenum [4] that is installed in an anechoic room. Under these anechoic conditions, the normal operating conditions of the fan are reproduced in two steps. The input voltage of the fan motor is first tuned to be the same as the one when the fan operates inside the machine. Moreover the size of the plenum aperture is also adjusted until the fan rotating speed becomes the same as the one measured when the fan is in the cavity.

4.2. Power injected acoustically

Once the normal operating conditions are reproduced, the acoustic sound power of the fan is measured in the anechoic room. This power is supposed not to be affected when the fan is installed in the cavity. The acoustic power measured in the anechoic room is used as an input parameter of our model.

4.3. Power injected mechanically

The fan is supported by subsystem 6 which is fastened to the plenum. The fastening of that subsystem to the plenum imitates its fastening to the machine. The exact mechanical power injected when subsystem 6 is in the machine is approximated using the following method. η_6 being known from the measurement of damping loss factors, power injected mechanically into subsystem 6 is approximated by :

$$P_6 = \omega_o E_6 \eta_6 \qquad (9)$$

E_6, the energy of subsystem 6, is determined by :

MODELLING OF AN INDUSTRIAL MACHINE USING S.E.A.

$$E_6 = \frac{m_6}{Q} \sum_{k=1}^{Q} | V_{6k} |^2 \tag{10}$$

Where m_6 denotes the mass of subsystem 6, Q is the number of measurement points and V_{6k} is velocity of subsystem 6 measured at point k.

5. ENERGETIC VIBROACOUSTIC MODEL OF THE MACHINE

5.1. Modelling with AUTOSEA

AUTOSEA is used to build a theoretical model of the machine. It allows to build up the different required subsystems, to connect them and to compute the energy responses for user's defined applied sources. AUTOSEA has a built in library of S.E.A. elements such as beams, plates, cylinders that can be stiffened or not. The library of coupling loss factors allows for various kinds of coupling.

The required input data are :

- the geometrical description of the subsystems : area, length, thickness, connected length...

- the mechanical physical properties of the constitutive materials : mass density, Young's modulus, Poisson's ratio...

- the way the structures are geometrically coupled : right angle, straight line, by points, etc...

- the dissipation properties (damping loss factors) of each subsystem which are here the results of the measurements performed on the machine

- values for sources inputs : here one third-octave band acoustic power spectrum for input power in the cavity. The mechanical power input by the fan into its support is here imposed indirectly by providing to AUTOSEA the velocity spectrum on the 6th subsystem.

Starting from the input data defining our machine, AUTOSEA automatically computes theoretical coupling loss factors : it calculates the transmission loss coefficient between two semi-infinite plates and then derives the coupling loss factors using a diffuse vibrational field hypothesis. The relevance of these theoretical values is checked by comparison to the measured values.
The machine is split into a set of inter-connected plates. These are coupled with the cavity already mentioned and with a 2D cavity. The 2D cavity is introduced in the model to take into account a parallelepipedic cavity of the machine. The thickness of that cavity is so small that no measurement can be performed in it.
For some particular subsystems, a stiffened plate model is selected to take into account the presence of stiffeners on the edges. Plate structures are coupled along their edges. The structural coupling loss factors are selected to get continuity of stresses on a line from one plate to the other at a right angle, which is relevant with the physical coupling of sub-systems in the machine.

5.2. Comparison between measurements and predictions

5.2.1. General comments

Comparing predicted average velocities for all the subsystems with the results provided by analog test configurations, leads to the following conclusions : both the structural and acoustic energy paths are accurately predicted by S.E.A.. As expected, at low frequencies (under 200 Hz), the difference beween test and prediction spectra increases and might reach 5 decibels, although the comparison of trends remains acceptable.

5.2.2. Comparison of sound power levels

The sound power level of the machine is measured in third-octave band using intensity. The measurement is performed automatically by a robot [5]. During the measurement, the machine is mounted on the floor. It is enclosed in a volume limited by the floor and a parallelepipedic measurement envelop. The component of the intensity vector, normal to this envelop, is measured at 252 points. Integration of that component on the measurement surface provides the sound power level. That measurement is performed for the five operating conditions of the machine.

As shown in figure 1, the external boundary of the machine is made of subsystems four, eight and nine. Acoustic power P_{rad} radiated to the outside may then be computed as :

$$P_{rad} = \omega_o \left(\eta_{4\infty} E_4 + \eta_{8\infty} E_8 + \eta_{9\infty} E_9 \right) \qquad (11)$$

Where $\eta_{i\infty}$ denotes the coupling factor between subsystem i and the outside, taken to be semi-infinite. AUTOSEA calculates vector $[\ E\ ]_1^N$ from which energies E_4, E_8 and E_9 are extracted. It provides theoretical values for the $\eta_{i\infty}$. It computes P_{rad} according to (11).

Figure (2) compares the sound power levels (integrated from 200 to 2500 Hz) measured by the robot and computed by AUTOSEA. The comparison is displayed for the five operating conditions of the machine. Averaged on the five operating conditions, the discrepancy between the two quantities is about one or two decibels.

6. CONCLUSION

The S.E.A. vibroacoustic model of an industrial machine was built. It foresees the sound power level with an average error about one to two decibels for the five operating conditions of the machine. Although rough, it takes into account some of the main design characteristics. For instance, the powers injected mechanically and acoustically by an internal source of the machine are taken into account. In terms of analysis, the S.E.A. model shows that the structural path is neglectable in front of the direct acoustic path. The simulation of usual noise reduction techniques suggests to treat the acoustic path first, to reduce fan noise if possible, and to optimize the acoustic treatment of the fan cavity. Completed with data about the simulated noise reduction costs, it might help the manufacturer in making up a decision on noise reduction.

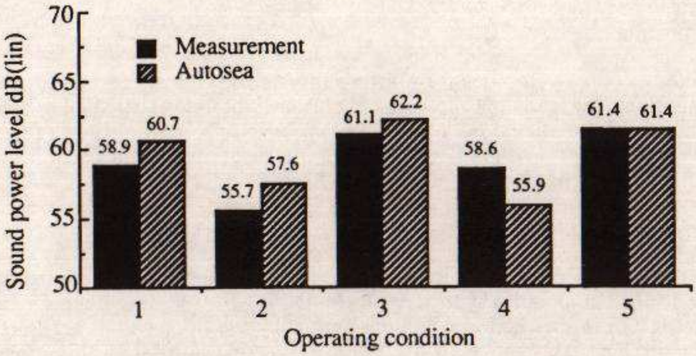

Figure 2 : Overall sound power levels measured by the robot and computed by AUTOSEA
Comparison is displayed for the five operating conditions of the machine

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