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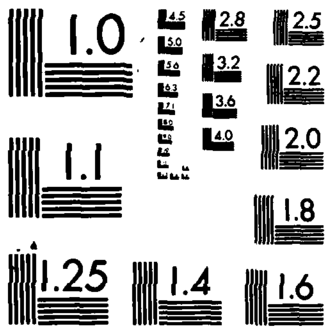

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COMPUTATION OF POWER FLOW IN POINT CONNECTED DYNAMICAL SYSTEMS

BY

J H JAMES

Summary

Power input by time-harmonic forces and power dissipated in a component subsystem are found from the displacements and reaction forces which are obtained numerically by a computer program for dynamic stiffness coupling. Power flow in a system consisting of a finite beam mounted on an infinite water loaded plate is given as a numerical example in order to demonstrate the usefulness of the program as a research tool for power flow calculations. Additional keywords: Great Britain; SEA (Statistical Energy Analysis); FORTRAN.

ARE (Teddington)
Queen's Road
TEDDINGTON Middlesex TW11 OLN

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1. INTRODUCTION

Among those methods developed for analysing power flow in complex dynamical systems the method of statistical energy analysis (SEA) has received most attention. It is a tool for calculating, in a statistical sense, the average response of a complex system in terms of a minimum number of parameters such as the hysteretic loss factors, coupling loss factors and modal densities of its component subsystems. These parameters can rarely be obtained theoretically, and it is found that a large number of measurements are usually required for their accurate determination, thus, apparently, destroying the simplicity of the method. It is thought that SEA, which must be regarded as an empirical science, is best suited to studying changes in existing systems rather than for the making of predictions at the design stage. The SEA method is discussed in detail in Lyon's text [1]. Atkins [2] at ARE(Teddington) has written a general purpose Fortran computer program for SEA analysis.

The physics of 'exact' power flow in simple dynamical systems has been investigated analytically by Goyder & White [3] in a series of informative papers. Their first paper gives, in tabular form, closed-form expressions for the mechanical power transmitted to an infinite beam and infinite plate by prescribed time-harmonic forces or displacements; their second paper investigates the power input to an infinite plate by an attached beam which is excited by forces; and their third paper investigates power flow in simple isolation systems in which the machine is modelled as a mass which is connected by a spring to an idealized foundation. This important work on power flow has been extended by Pinnington & White [4] and Pinnington [5] to the realm of experiment, and the modelling of the machine and its foundation as resonant Bernoulli beams in flexure. This work has demonstrated that the frequency averaged power input to a finite system is, at a sufficiently high frequency, well approximated by the power input to the related infinite system. This could have important implications when analysing practical isolation systems whose lack of known structural detail renders exact analysis all but meaningless at high frequencies.

While the SEA method in itself is not well suited to design studies or predictions at low frequencies, the exact methods of computing power flow are deficient due to the absence of suitable computational methods for analysing complex dynamical systems. Thus, the principal motivation for the work contained herein lies in the requirement for reliable methods for calculating power flow over a wide range of frequencies, especially in isolation systems which are mounted on fluid loaded foundations. These dynamical systems are usually designed to minimize force or velocity at the isolation points, whereas it may be more profitable to design systems for minimum power flow, either in the foundation or its surrounding fluid in which it may take the form of acoustic radiation.

2. POWER FLOW IN SUBSYSTEM

Figure 1 shows an isolated subsystem which is a member of a complex point connected dynamical system. At each of the N connection points to other dynamical systems and/or external forces, there are, in general, 6 degrees of freedom

$$\{X\} = \{u_x, u_y, u_z, \theta_x, \theta_y, \theta_z\}^T \tag{2.1}$$

comprising 3 displacements and 3 rotations, and 6 reaction or external forces

$$\{F\} = \{F_x, F_y, F_z, M_x, M_y, M_z\}^T \tag{2.2}$$

comprising 3 point forces and 3 point moments. From here on in this report, the word 'forces' may imply forces and/or moments, and the word 'displacements' may imply displacements and/or rotations.

The mechanical power dissipated by structural damping and acoustic radiation is

$$P = \mathrm{Real}\left(\sum_{j=1}^{N} \{F_j\}^T \{\dot{X}_j^*\} \right) > 0 \tag{2.3}$$

where the customary multiplication factor of one-half has been omitted because force amplitudes are usually specified in terms of their rms values. $\{\dot{X}_j^*\}$ is a column vector of the complex conjugate of the velocities, viz.

$$\{\dot{X}_j^*\} = +i\omega\{X_j^*\}, \text{ for time variation } \exp(-i\omega t)$$

or (2.4)

$$\{\dot{X}_j^*\} = -i\omega\{X_j^*\}, \text{ for time variation } \exp(+i\omega t)$$

The individual terms in Equation (2.3), viz.

$$P_j = \mathrm{Real}(\{F_j\}^T \{\dot{X}_j^*\}) \tag{2.5}$$

may have separate physical meaning because the power balance equation for each subsystem requires that the power dissipated is equal to the power transmitted into the subsystem minus the power transmitted from the subsystem, and this quantity is always positive. The power flow at point j may be quite complex, for example:

(a) If point j is not connected to other subsystems, but is a point where external forces are applied, then positive P_j means that power is transmitted to the subsystem by the external forces while negative P_j means that power is absorbed by the external forces. Thus it is important to realize that external forces can absorb power from, as well as transmit power to, a subsystem. In the former case it is necessary that the subsystem and/or other connected subsystems are subjected to other external forces. The sum of the separate powers input by external forces in the various subsystems must be positive.

(b) If point j is connected to other subsystems, and there are no external forces applied at this point, then $\{F_j\}$ are reaction forces whose vector sum over all subsystems that connect at point j must be zero. For the single subsystem under consideration, P_j is positive if power is transmitted to it at the connection point j, and P_j is negative if power is transmitted from it at this point. If the other subsystems attached to point j are isolated from forces, which means that they are not connected either directly or indirectly to other subsystems with external forces, then P_j will be negative. If one or more of the attached subsystems at point j are not isolated from external forces, then P_j may either be positive or negative, as power may either be transmitted to or from the subsystem at point j. If the subsystem is isolated from external forces at all connection points except point j, then P_j must be positive as power will be transmitted to the subsystem at the connection point j.

(c) If point j is connected to other subsystems and there are external forces applied at this point, then $\{F_j\}$ are the reaction forces whose vector sum over all subsystems that connect at point j must be equal to the external forces. Hence, the total power transmitted at point j to all connecting subsystems may either be positive or negative as in (a) above. Additionally, the power P_j transmitted to the subsystem under consideration may either be positive or negative. For the particular case in which the subsystem is isolated from external forces, except at connection point j, then P_j must be positive as power will be transmitted to the subsystem. It may help, conceptually, to create a null connection point at a vanishingly small distance from the point j: the external forces are then applied to this point and the statements in (a) and (b) above are then applicable.

The computation of power flow in a complex dynamical system is thus reducible to the computation of the displacements and reaction forces at the connection points. The total power dissipated in a selected subsystem is given by equation (2.3) whose individual terms, equation (2.5), have physical meaning as the power transmitted to or transmitted from a connecting subsystem. In fact, the individual terms can be thought of as the sum of powers transmitted by individual reaction forces.

3. ACOUSTIC POWER

When the surface of the subsystem shown in Figure 1 contacts an acoustic fluid the mechanical power dissipated, as defined by equation (2.3), is

$$P = P_d + P_r \qquad (3.1)$$

where P_d is the power dissipated by structural damping, and P_r is the power dissipated in the form of acoustic radiation, which is of central importance in noise control problems. For a closed surface S surrounded by an acoustic fluid

$$P_r = \text{Real} \int_S p(S)\dot{x}_n^*(S)dS \tag{3.2}$$

where p(S) and $\dot{x}_n(S)$ are, respectively, the surface pressure and normal velocity. Alternatively, if the far-field pressure is known, usually from an asymptotic expansion, as

$$p(R,\theta,\phi) = A(\theta,\phi)\exp(ikR)/R \tag{3.3}$$

then

$$P_r = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} [|A(\theta,\phi)|^2/\rho c]\sin(\theta)d\theta d\phi \tag{3.4}$$

which double integral is evaluated numerically by a quadrature formula such as Simpson's rule. (R,θ,ϕ) are spherical polar coordinates, ρc is the characteristic impedance of the fluid, and $A(\theta,\phi)$ is the angular distribution of the sound field.

For researchers working in the field of fluid structure interaction the text written by Junger & Feit [6] is the standard source of information if closed-form expressions for $p(R,\theta,\phi)$ are required for the special cases of infinite plate, infinite cylindrical shell and finite spherical shell. Few useful approximations are available for the far-field sound radiation of finite bodies excited by prescribed forces, despite the considerable research effort that has been expended in this area. However, for general studies the aforementioned geometries can be made to provide suitable approximations.

4. COMPUTATION OF FORCES AND DISPLACEMENTS

Program COUPLE is a well-established and versatile Fortran program for computing the time-harmonic forced response of point connected dynamical systems by the method of dynamic stiffness coupling. It was designed and written at Imperial College, London, by Sainsbury [7], and it has been periodically updated and extended at ARE(Teddington) [8] where it runs on a PDP-11. The program assembles the dynamic stiffness matrices of basic subsystems to form a system dynamic stiffness matrix whose inverse enables the displacements at the connection points to be found, when the excitation forces are prescribed. The frequency dependent dynamic stiffness matrix, $[D(\omega)]$, of a subsystem relates displacements and forces on that subsystem by the matrix relation

$$[D(\omega)]\{X\} = \{F\} \tag{4.1}$$

where, for the subsystem of Figure 1 which has 6 degrees of freedom at each connection point, {X} and {F} are, respectively, displacement and force vectors of length 6N. However, COUPLE requires specification of only those degrees of freedom that participate in the forced response. Degrees of freedom omitted from the analysis can be regarded as 'free' connections. This is sensible because the special cases of one- and two-dimensional motions, for example, would otherwise be overdetermined. For the finite element method $[D(\omega)]=[S]-\omega^2[M]$, and if it is obtained by experiment then it is the inverse of the receptance matrix.

In the context of COUPLE a basic dynamical system is simply a subsystem whose dynamic stiffness matrix is known either analytically, numerically or experimentally. The following basic dynamical systems are known to the program:

(a) Frequency independent mass, stiffness and damping matrices of simple dynamical systems.

(b) Three-dimensional mass and spring elements with nodes that may be offset from the connection points.

(c) Euler-Bernoulli and Timoshenko space frame elements with offset nodes: special cases of inplane and out of plane motion with options for axial extension and torsion. These elements are exact, i.e. the elements of their dynamic stiffness matrices are known transcendental functions.

(d) Infinite beam and infinite fluid loaded plate.

(e) Eigenvalues and suitably normalized eigenvectors obtained from finite element computer programs.

(f) Receptance or stiffness type data stored on a disk file by auxiliary programs or by COUPLE itself during a previous job. Thus, experimental data, user generated subsystems and substructuring may all be used.

Program output is to a printer and disk file for subsequent processing and plotting. The output, at each frequency of a linear or logarithmic frequency sweep, and for each set of prescribed force conditions, consists of selected values of the following:

(a) Displacements at the connection points, and transmissibilities which are defined as the ratio of responses at selected degrees of freedom. The displacements enable computation of the input powers, and allow substructuring via receptance matrices.

(b) Forces transmitted to ground, viz. reaction forces at selected degrees of freedom whose motions are constrained to zero. Reaction forces at selected degrees of freedom of a subsystem. The reaction forces permit calculation of the power that is dissipated in the subsystem.

For the PDP implementation there is allowed a maximum of 60 degrees of freedom together with a maximum of 60 individual subsystems. This is not unduly restrictive because (a) some of the subsystems are exact, thus rendering unnecessary subdivision as the frequency is increased; (b) substructuring is possible;

(c) only those degrees of freedom at subsystem connection points are required; and (d) the structural dynamics modelling process should be regarded as phenomenological rather than one-to-one because there is seldom close agreement between theory and experiment at frequencies above the resonant frequencies of the first few modes.

5. COMPUTATION OF POWER

Fortran programs have been written to process the disk file produced by COUPLE in order to:

(a) Calculate the mechanical power input by selected prescribed excitation forces, and the power transmitted to a specified subsystem by selected reaction forces.

(b) Calculate the acoustic power radiated by an infinite point or line excited plate, together with the maximum pressure and the pressure normal to the plate surface. Additional acoustic subsystems are to be added on an opportunity basis.

Output is to a printer and to a disk file for subsequent processing and plotting. The program specifications are documented elsewhere [8].

6. NUMERICAL EXAMPLE

Figure 2 shows an 'Euler-Bernoulli' steel beam of mass 100kg which is attached by 3 springs to an infinite water loaded steel plate, of thickness 0.01m. The steel plate has 9 point masses, each of 10kg, attached to it. The springs do not exert moments either on the beam or on the plate. The beam is excited by a vertical time-harmonic point force, of magnitude 1kN rms, which is applied at the centre of the beam. The system is modelled by 15 COUPLE subsystems comprising 2 beams, 3 springs, 9 point masses and a water loaded plate. There are, for this particular model, 15 degrees of freedom comprising 12 vertical displacements (numbered 1-12) and 3 rotations (numbered 13-15). The material and geometric constants, in SI units, chosen for this simplified machinery isolation system are:

Beam:	$E=19.5\times10^{10}$ $\rho=7700.0$ $\eta=0.01$
	$L=1.0$ $A=0.013$ $I=1.41\times10^{5}$
Spring:	$S=0.333\times10^{8}$ $\eta=0.01$
Point masses:	$m=10.0$, with separation$=0.5$
Plate:	$E=19.5\times10^{10}$ $\sigma=0.29$ $\rho=7700.0$
	$h=0.01$ $\eta=0.02$
Water:	$\rho=1000.0$ $c=1500.0$

E is Young's modulus, ρ is density, η is the hysteretic loss-factor, L is the length of the beam whose cross-sectional area is A and whose moment of area in bending is I, S is the stiffness of each spring, m is the mass of each of the point masses, σ is Poisson's ratio of the plate whose thickness is h, c is the sound velocity in water.

If the isolation system were mounted on a rigid foundation rather than the elastic plate, then the response spectra, in the frequency range to 1kHz, would be dominated by two sharp peaks; the first at 150Hz being due to the mass of the beam acting on the stiffness of the springs, and the second at 650Hz being due to the fundamental bending resonance of the beam. For the case in which the beam is mounted on the elastic plate, the power input by the driving force, the power transmitted to the plate and the radiated acoustic power are shown in Figure 3. Also given for comparison purposes are the corresponding values for a uniform plate which is excited directly by a 1kN rms force: these curves are smooth because the impedance of a fluid loaded plate is resistive with a very small stiffness component, which means that a resonant response is not possible.

The mechanical input power of the machinery isolation system is dominated by a peak at approximately 665Hz, which is due to the first bending resonance of the beam behaving as an almost free body. At frequencies below 500Hz the humps that appear in the spectrum are mainly due to interactions between the point masses, but the beam mass and spring stiffness contribute to the first maximum at 100Hz. These interactions are not too important above 500Hz because the beam is partially isolated from the plate, which means that the input power is controlled by the beam's properties. The power transmitted to the plate is not much different from the input power at frequencies up to 500Hz, but thereafter the power transmitted is increasingly less than the power input.

The power dissipated as acoustic radiation is less than 1% (20 dB down) of the power transmitted to the plate. Thus, at least 99% of the power transmitted is dissipated by structural hysteresis damping as a slightly damped 'free wave' propagates parallel to the plate surface. The power carried by this wave may partially be converted to acoustic radiation power if remote impedance discontinuities are present on the plate's surface. With the exception of the maximum at 100Hz, the humps in the spectrum are characteristic of those obtained by interactions among symmetrically placed masses whose forces of constraint may either enhance or reduce the radiated power, depending on their phase relations.

7. CONCLUDING REMARKS

The power flow in a point connected dynamical system is computed from displacements and reaction forces that are stored on disk file by a well-established Fortran program for dynamic stiffness coupling. A numerical example of power flow in an idealized machinery isolation system, attached to a water loaded plate, has demonstrated the potential capability of the Fortran programs as useful numerical tools for research in the field of fluid-structure interaction. It is believed that these programs are the most comprehensive available for power flow calculations. The following theoretical work is proposed as follow-up projects in order to establish their practical value:

(a) Numerical investigation of power flow in a realistic model of a machinery isolation system which is mounted on a fluid loaded foundation. The system may or may not have several 'vibration shorts' and attached dynamic vibration absorbers. Of particular importance should be the identification of dominant transmission paths to the fluid and the effect of damping applied either continuously over subsystems or locally at joints.

(b) Modelling of the isolation system at high frequencies with 'infinite' elements in order to simplify the computation of power flow. Comparison of numerical results with those obtained from the SEA method.

8. ACKNOWLEDGEMENT

The not inconsiderable effort of M.G. Sainsbury in designing and writing the Fortran program COUPLE is much appreciated. J.F. Hardenberg recommended its use at ARE(Teddington), where E.J. Clement has helped to implement many of its updates and extensions since 1976, on a PDP-11 computer running under the RT-11 operating system.

J.H. James (PSO)
June 1985.

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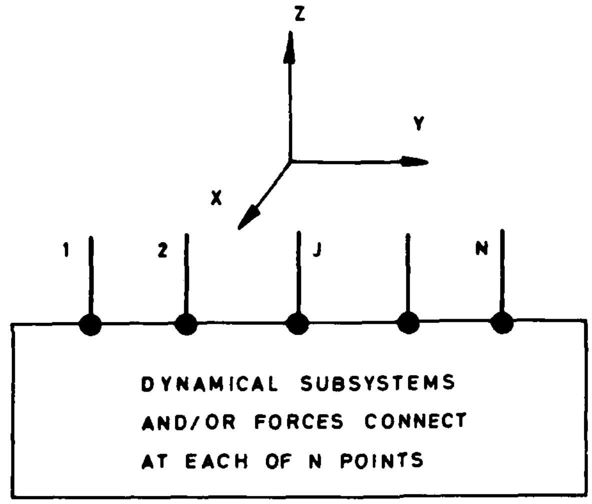

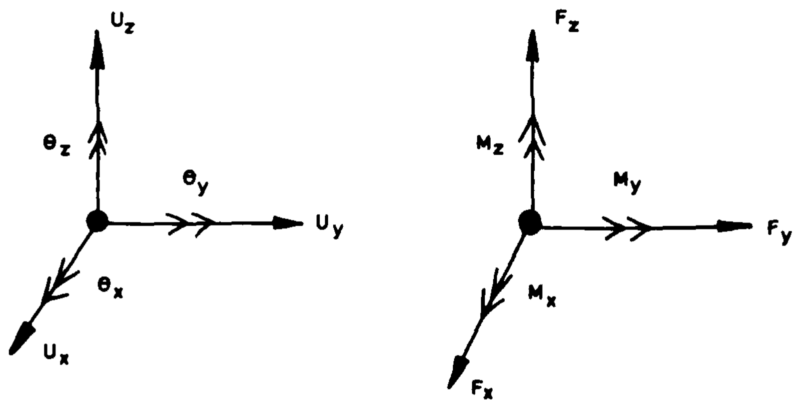

THE STANDARD SIGN CONVENTION FOR THREE - DIMENSIONAL POINT CONNECTED SUBSYSTEMS HAS BEEN ADOPTED

FIG. 1 DYNAMICAL SUBSYSTEM AND SIGN CONVENTION

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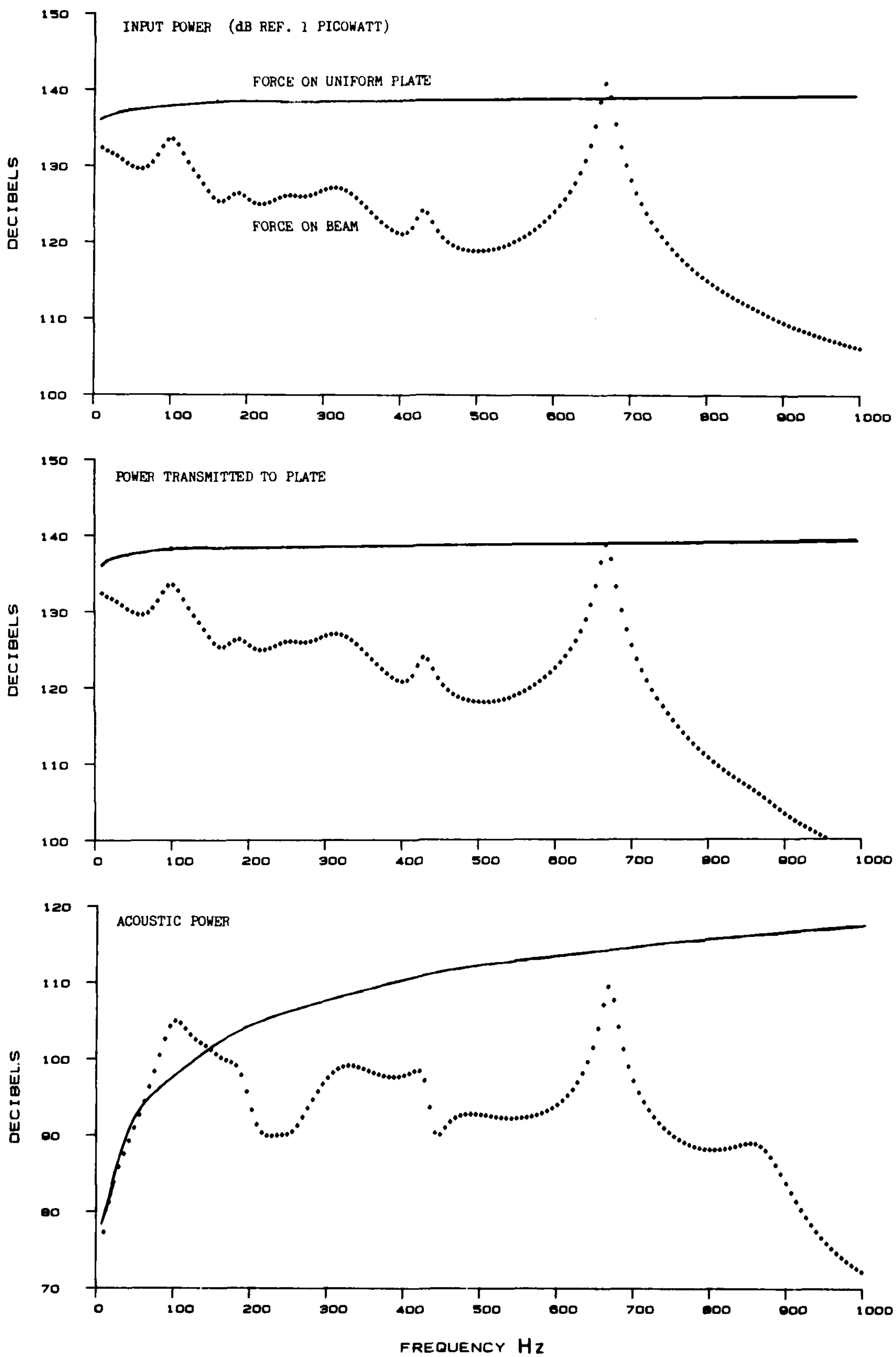

FIG. 3 POWER FLOW IN MACHINERY ISOLATION SYSTEM ......
POWER FLOW IN UNIFORM PLATE ———

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