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SOME METHODS FOR EVALUATING SOUND AND VIBRATION TRANSMISSION PATHS IN LARGE INDUSTRIAL & MARINE ENGINEERING ENVIRONMENTS.

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INTRODUCTION.

The specific techniques described in this paper are not claimed to be novel; rather the intention is to address a particular type of noise problem involving multiple transmission paths, such as can frequently be encountered in industrial and marine environments, to show how an appropriate combination of techniques can be used to quantify these transmission paths. The intended method of reducing the noise source may be either active or passive; the overall approach is perhaps particularly suitable for evaluating the likely effectiveness of using active cancellation techniques, without any need to embark on the installation of expensive hardware until one is confident of obtaining satisfactory performance. The method is particularly appropriate for use under circumstances where it is not possible to quantify separately the effects of individual source components, but only their cumulative total effect; (it is naturally assumed that if at all possible, one would attempt to quantify individual sources by separating them out and estimating their contributions).

An example of the type of problem under consideration is illustrated in Figure 1. A large vibrating machine, giving rise to both vibration transmission and a direct airborne component, is mounted in a large structure (which might be an industrial building or a ship), and radiates unwanted noise into the external environment. It will be assumed that this noise is radiated at a single discrete frequency or frequencies; if the individual sources represent independent uncorrelated components, then one could use conventional coherence techniques to determine the contributions to the far field arising from each individual source. However it is not often appreciated that one of the most difficult types of problem to tackle can be one where multiple sources generate a single common frequency, particularly when there is no convenient method of decoupling any individual sources to quantify its pecise contribution. The fact that the sources are phase-locked can give rise to complicated interference patterns, with the result that measurements in the far field may vary dramatically in intensity over comparatively small length scales, and unless meticulous and methodical techniques are used, it can be extremely difficult to predict the precise effects arising from modifications to the sources.

Under many circumstances, it may also be difficult to obtain easy access to seating structures under the machine in order to carry out direct excitation with large shakers; in such circumstances it is often useful to resort to Reciprocity Techniques to obtain the necessary transfer functions, and a discussion of various possibilities in this respect will be given. However, the analysis will be presented on the initial assumption that the basic transfer function measurements are obtained using direct methods of excitation. It will also be assumed initially that the observation of the far field "response" is confined to measurements of structural acceleration, but an extension of the techniques to observations in air (or water) will then be proposed.

ANALYSIS.

The central analysis is essentially that proposed by Kinns [2], and represents an improvement over methods of describing a machine by a single equivalent force, as has been proposed by T. ten Wolde. The assumption is that there are unknown excitation forces applied to M identifiable transmission paths, (for example at the feet of mountings of terminations of flexible connectors.) At the same time it will be assumed that there are N observation points at which the transmitted signal can be observed. Furthermore, it will be assumed that there may in practice be more than M sources contributing to the radiated field (for example, an airborne component which cannot easily be quantified). An essential requirement is that the number of ovservation points N should significantly exceed the number M of forces to be determined. Clearly if N is less than M a unique solution cannot be obtained; there will be a large number of possible combinations of M forces which could account numerically for the N observations. Similarly, if N=M, then one should be able to solve for a unique set of M forces to account for the observations, but if it is known that there exist additional unidentified sources, the resultant set of M forces is extremely unlikely to be a correct description of the true source distribution. So the only acceptable approach is to ensure that the number of observation points N significantly exceeds the number M of sources to be quantified; the greater the number of observation points, then the greater the precision with which these M sources will be deduced. Essentially the technique amounts to finding the best "average" description of M sources which will account for the N observations. The residual "error" in each observation then represents a minimum value for the net effects of any additional sources which have not been quantified.

Given the M force inputs and the N observation points, let T_{nm} $(1 \leq n \leq M, 1 \leq n \leq N)$ represent the (measured) transfer function matrix between the two sets of points. Let the acceleration response at the observation points when the machine is running be 'a_n' $(1 \leq n \leq N)$ Then the objective is to find the set of forces F_m which account for the observations as accurately as possible i.e.

Minimise $$\sum_{n=1}^{N} \left| a_n - \sum_{m=1}^{M} T_{nm} F_m \right|^2 \text{ by choice of } F_m \quad (1)$$

The optimal choice of F_m is obtained by differentiating this expression, and results in a set of M simultaneous equations

$$\sum_{n=1}^{N} \left\{ a_n - \sum_{m=1}^{M} T_{nm} F_m \right\} T^*_{np} = 0 \qquad (1 \leq p \leq M) \quad (2)$$

If one now constructs the M by M matrix, $\underline{\underline{D}} = [\sum_{n=1}^{N} T^*_{np} T_{nm}]^{-1}$, the solution for each F_m becomes

$$F_m = \sum_{p=1}^{m} D_{mp} \left(\sum_{q=1}^{N} a_q \, T^*_{qp} \right) \quad (3)$$

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The residual response at each observation point is then given by

$$\left[a_m - \sum_{m=1}^{M} T_{nm} \sum_{p=1}^{M} D_{mp} \left(\sum_{q=1}^{N} a_q T^*_{qp} \right) \right]^2 . \qquad (4)$$

and this residual contribution is assumed to be due to the other unknown source(s).

It should be noted that this analysis requires knowledge only of the amplitude (and phase) of the response at each observation point, together with the transfer function matrix T_{nm} from the M known source positions. It can be used immediately to deduce the maximum improvement which could be achieved by isolating any one or all of these individual transmission paths, and in particular it automatically defines the absolute maximum performance which could be achieved by installing active force actuators (of controllable amplitude and phase) at each of the M positions. Under such circumstances, the expression for the residual field represents the best achievable performance.

MEASUREMENT OF TRANSFER FUNCTIONS.

It will be observed that a feature of the method is that it involves manipulating a large number of transfer functions (NxM). Given modern processing facilities, the computational effort involved in performing the calculations should not be regarded as prohibitive. However, it is absolutely imperative that an easy and efficient method should be devised for obtaining the data in the first place. The author first encountered this type of problem in the context of using large matrix arrays of accelerometers to relate structural vibration to radiated sound while working at YARD [4]. It was found to be convenient to use Reciprocity Techniques, whereby the excitation was applied instead at the "observation" points and the particular source points under investigation were permanently monitored in parallel using accelerometers, the signals from these being recorded on a 14-channel tape-recorder. A transient testing technique, using repetitive inputs with a hand-held or electrically driven hammer on a "wandering lead" was used, and this enabled a large number of "observation" points to be surveyed in very rapid succession. At that time, two problems were encountered. First, restrictions on available processing power limited the extent to which post-processing could be easily carried out, with the result that methods of pre-processing the data had to be devised to simplify the overall task. As already remarked, this particular constraint no longer applies. However, the second constraint was one of obtaining a sufficiently large amplitude of response at low frequencies, while accurately monitoring the input forces. The author carried out numerous experiments with a variety of exciters, including large electric and pneumatic chipping hammers. (The advantage of such devices is that they are comparatively easily portable, while the necessary power or compressed air supplies are usually readily available on an industrial site.)

However a problem was encountered, in that although such devices undoubtedly provided an easy and convenient method of obtaining large input forces, the severity of the impacts was such that piezoelectric force gauges could not withstand the stresses imposed, and they ceased to function after continuous use. An off-the-shelf electric impact exciter was eventually purchased which represented a compromise solution; although its force transducer was purposedesigned for the task, the input force levels were considerably lower than those which had been achieved with the pneumatic devices.

With hindsight, it is proposed that this problem could be tackled in the following manner. The author had constructed a very simple and light hand-held hammer, using a miniature B&K force gauge to provide a very low inertial head-mass, and it was found that this gave extremely accurate results for local measurements of point and transfer impedance, using a technique of rapid repetitive hammering to produce a continuous random input signal. However, this was obviously inappropriate for measurements over a large distance, since the input signals were of far too low an amplitude. But the local structural response can be accurately calibrated using this hand-held hammer, and having obtained this calibration, the same nearby accelerometers can then be used to monitor the response under excitation from a much larger pneumatic hammer. No attempt should be made to measure directly the input forces in the latter case; instead the response of the pre-calibrated structure should be used to deduce the forcing levels, and the relevant measurement becomes simply the attenuation from the nearby accelerometers to the remote monitoring points. From this data, together with the local transfer functions, one can deduce the overall transfer functions to the more remote points (Figure 2). In this way, one should be able to combine the ease and accuracy of using a miniature hand-held hammer, with the undoubtedly high levels of input forcing (and ease of manouevreability) obtainable with a pneumatic hammer.

It has been assumed so far that the "observation" points are also located at positions on the structure; however a very likely situation is that one might wish to reduce the airborne sound pressure level external to a building, in which case the relevant transfer functions become those relating the structural input forces to the airborne SPL. Under such circumstances, a less well-known version of the Reciprocity Theorem might be applied, in a form which has been used by T. ten Wolde in ship vibration testing [1]. This can be expressed as follows. Let a force input of magnitude F applied to the structure gererate a sound pressure level p at the observation point. If instead a volume source Q is placed at the far-field observation point, such that it induces an acceleration response 'a' in the structure, then

$$\left(\frac{p}{F}\right) = \left(\frac{a}{\dot{Q}}\right) \quad \text{where } \dot{Q} \text{ denotes time derivative}$$

So a convenient method of obtaining the necessary structural force to far-field noise transfer functions is in fact to excite with a simple volume source in the far field and measure the acceleration response induced at the various mounting points of the (stationary) machine. The problem now becomes one of generating an adequately large, yet conveniently moveable, volume source. Calculations indicate that to obtain measureable structural acceleration responses, one requires a volume source capable of generating 80dB SPL at typical distances of say 100m. One could achieve this by using an array of loudspeakers; if one wished to concentrate on a particular discrete frequency one could arrange to drive these into a tuned "high Q" enclosure, taking the form of either an enclosed resonator [4] or 1/4-wave length of ducting, in which case one could reduce significantly the number of loudspeaker elements required. However, one particular possibility might be worth considering. Since diesel engines represent particularly efficient low frequency sound generators, one might simply position a lorry at appropriate points in the far field and run the engine at the necessary speeds, preferably with a long, large bore, unrestricted open exhaust pipe!! Its volume source strength could be calibrated with a nearby microphone, and providing there were no difficulties of access, the problem of moving the source quickly to a number of different survey points would be solved automatically!

CONCLUDING REMARKS.

It has been argued that under circumatances where a vibrating machine generates an unwanted sound field via a multiplicity of transmission paths, and where the excitation occurs at a discrete frequency or frequencies, the observed far-field can consist of a complex interference pattern where the precise contributions due to individual sources may be difficult to quantify. An extension of a technique first proposed by Kinns has been suggested, in which, by exciting with a far-field volume source and measuring the induced acceleration response under the machine at the different "source" points, one can obtain a "best estimate" of the forces being applied by the machine at these points. An expression for the residual response in the far field can then be obtained, which represents a minimum value for the contribution due to direct airborne radiation, and would also represent the maximum performance achievable by active cancellation of the excitation forces.

REFERENCES.

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Figure 1.

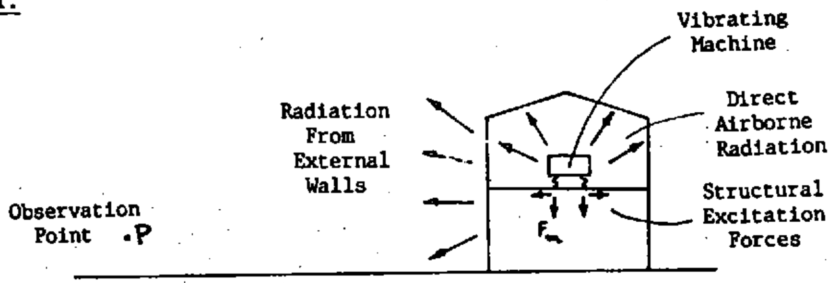
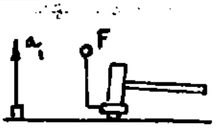


Figure 2.

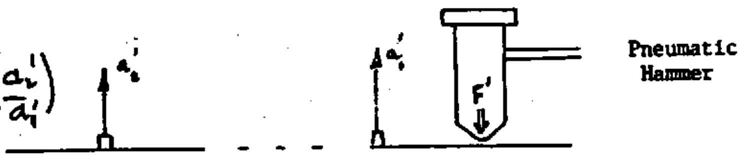
a) Local Structural Calibration



$$T_1 = \left(\frac{a_1}{F}\right)$$

b) Attenuation Measurements to Remote Points

$$A = \left(\frac{a_2'}{a_1'}\right)$$



Desired Transfer Function $T_2 = \left(\frac{a_2'}{F'}\right)$

$$= \left(\frac{a_2'}{a_1'}\right)\cdot\left(\frac{a_1'}{F'}\right)$$

$$= A . T_1$$