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DIAGNOSTICS IS A PROPER FIELD FOR NOISE CONTROL ENGINEERS

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The noise and vibration produced by machines have Tong been of concern to noise control engineers. The emphasis of such concern has been the effect of noise on people, whether hazardous or simply objectionable. The use of vibration signals to reveal operating characteristics of the machine is a new and requires a new set of measures of both the characteristics of the noise signals and the effects of the machine structure on these signals. This paper discusses the relation between noise studies and diagnostics in terms of their similarities and differences, and suggests that diagnostics is a proper field of study and work for noise control engineers.

I. Comparison of diagnostics and noise reduction

When mechanism operate within a machine, forces are generated that produce vibratory motions. These vibrations are transmitted through the machine and result in exterior surface vibrations and radiated sound. Whether the sound or vibration is of concern as a noise problem or is to be used for fault detection in a diagnostic system, these features of excitation, transmission, and radiation are important. The similarity of these basic aspects of noise problems and diagnostics is evident [1].

The greatest differences between diagnostics and noise lie in their respective goals. A machine operating properly and without faults can still be very noise, and a machine that has developed a major fault can still operate quietly. Signal features that may be important for diagnostics, such as phase, are generally ignored in noise problems. Signal energy in the speech bands, so important in noise problems, has no special role in diagnostics.

Although both noise reduction and diagnostics represent established activities, there has been relatively little interaction between these fields. This results partly from a difference in goals and partly due to differences in the frequency range in the signals of interest. But more interest in source noise control and newer signal processing methods that can gain more information from broad band signals have given emphasis to areas that have features in common. It is natural, therefore, that these two specialities of engineering acoustics — noise control and diagnostic analysis — should become more closely related subjects of research and application.

II. Goals: noise reduction vs. diagnostics

The goals of a noise reduction program generally include one or more of the following [2]:

Reduction of hazard — such as hearing loss, hypertension, etc. This is a traditional goal of noise control — it is of lesser concern in some countries at present because of decrease in regulatory activity.

Reduction in functional impairment such as speech interference, task performance, etc. This area continues to be an important goal for noise reduction since users of machines must be able to function in the environment of the machine.

Increased acceptability of sound — such as consumer satisfaction: and the related goal — enhanced product image.

These last two goals are occasionally of interest to manufacturers of consumer products and represent areas in which noise reduction engineering could be of greater service in product design. Helping manufacturers to meet these goals will require new approaches in product sound evaluation — stepping away from *A*-weighted intensity measures to evaluation procedures that may be very product specific.

The goals of diagnostics are usually thought of in positive terms:

To determine presence of faults, or perhaps, more generally,

To determine operating parameters,

since out of bound parameter values (fuel charge, clearances, ignition timing) can also be considered to be faults. It is perhaps more accurate, however, to describe these goals in a rather negative manner:

Not to make mistakes.

There are two kinds of mistakes one can make in diagnostics:

Type 1 error: There is no fault, but a faulta condition is declared.

Type 2 error: There is a fault, but a safe condition is declared.

Depending on the situation, the relative penalties for making each kind of mistake can be quite different. Type 1 errors can be very costly if a production process is needlessly interrupted. Type 2 errors can be expensive in security systems.

It is clear that meeting psychoacoustical criteria is crucial to realizing the goals of noise control. Since listening to machines is a traditional and practical method of diagnostics, some diagnostics system designers have sought to "do what the person does" in detecting faults. Although this approach can be successful in particular instances, it may lead to even greater efforts to "diagnose" the listener, i.e., to learn what the person is doing in making diagnostic judgements. In general, it will be better to spend this effort learning enough about fault related vibration generation and transmission in order to design the diagnostic system to detect and recover the appropriate signals.

III. Generators of vibration

Both diagnostics and noise analysis use power spectra of excitation sources as signals of interest. Diagnostics has generally used line spectra of rotating machinery to detect imbalance, misalignment, and other faults. Because the relative strengths of the spectral lines that correspond to shaft multiples are important the frequency dependence of the transmission path for such vibrations is also important [4].

Broadband, fullor third- octave spectra are of special importance in noise analyses, but they can also be useful for diagnostics. For example, impact and roughness in bearings produce broadband excitations and simple energy detection in these high frequency bands can indicate faults. The distinction between line and continuous spectra is not perfect, of course, since jitter in the occurrence of a *once-per-rev* impact can a transition from a line spectrum at low frequencies to a continuous spectrum at high frequencies.

The major division among approaches to determining source signatures is *empirical* vs. *analytical*. This is best exemplified by studies of *piston slap*, a noise or vibration pulse produced by piston and cylinder wall impact in diesel engines [5]. There have been a number of studies of the dependence of piston slap noise on ring clearance, cylinder pressure, piston/cylinder clearance, etc. An analytical study of this problem allows one to determine both spectra and temporal waveforms of the interaction force between piston and cylinder wall. The temporal waveform of the excitation source can have significant diagnostic value.

Whether the source *signature* of interest is an excitation spectrum or a temporal waveform it is unlikely that analytical or empirical procedures will be able to determine all signatures of interest. As in noise analysis, diagnostic procedures may be required to determine source properties from "output" data, the external machine vibration or sound radiation.

IV. Structural response of the machine

Noise analysis has typically taken a rather simplistic approach to structural noise transmission. Since signal phase and spectral details have relatively litle importance for noise, models such as Statistical Energy Analysis that provide estimates of the magnitude of a frequency and spatially averaged transfer function are widely used. Details of phase and magnitude are important in the performance of isolators, and in the energy injected into a structure by narrow band sources such as rotating components, but often a frequency averaged estimate is satisfactory.

As noted above, diagnostic systems may (or should) require much more detail in the knowledge of the transfer function.

The amplitude of individual line components, such as the meshing frequency of a gear, compared to other levels can reveal important features of machine performance. If these relative amplitudes are modified by the transmission path, their diagnostic value is reduced. It is partly for this reason that changes of these amplitudes over time may have more diagnostic value and such changes are frequently tracked in practical systems [6].

The recovery of source signatures from output data requires that we know the magnitude and/or phase of the transfer function much better than we need to for noise analysis [7]. We have noted the importance of the magnitude spectrum for an accurate determination of line spectra. The recovery of temporal waveforms requires a detailed knowledge of the phase spectrum, an almost unexplored area in structural transmission studies. Recent research has shed more light on the phase properties of transfer functions, but it is still not clear how the information that is needed to recover source signatures is to be obtained.

The need for detailed information on structural transmission raises a related issue of variability. A diagnostic system may be installed in a variety of machines and both the transfer function for vibration and the transducer mounting impedance can vary greatly. Thus, vibration spectra on machines of the same general type but that are different models or from different manufacturers may not be at all comparable [10]. This makes the use of vibration criteria based on vibration levels alone unreliable, particularly at frequencies above the first few machine resonances.

It is perhaps more surprising that transfer functions measured on nominally identical machines should show a great deal of variability in magnitude and phase, but they do [11]. This means that a diagnostic system designed for a particular machine model may have to be in some way "tuned" to each individual machine to which it is applied. This is beyond the capabilities of systems that are currently on the market, but research on this topic is being actively pursued [12].

V. Signal processing of vibration data

The vibration sensor location for noise studies may be closely specified, such as above an isolation mount, or loosely specified, i.e., at an "average" position on a housing or cover. Frequently, the band levels at a number of locations will be averaged in order to predict noise from the machine, or to correlate with predicted values.

There is a great deal more experience in relating vibration levels to noise than there is to machine faults. Perhaps for this reason, sensor locations and mountings for diagnostics tend to be highly specified. Current systems tend to use one transducer per machine element using observed and pick-up locations typically at bearing caps or shaft journals. More advanced systems will be required to have sensors placed at a greater distance from the source (*s*) and to use multiple sensors, but fewer than the number of sources to be diagnosed. This requires multi-dimensional source waveforms or spectra.

Our group at MIT has been using inverse filtering to recover source spectra and waveforms. The design of inverse filters is a key element to the success of this approach. A single source (diesel engine combustion pressure, for example) and sensor (accelerometer on the engine casing) requires an inverse filter that has a response that is just the opposite of the transmission path through the engine structure, both in magnitude and phase.

There will be a number of narrow bands in which the structure transmits very little energy (notches), so that noise contamination at the sensor is a problem. An inverse filter will have a great deal of gain at these frequencies and may, therefore, amplify output noise. It is possible to develop a criterion for a maximum gain that the inverse filter is allowed to have based on the signal to noise ratio at the output as estimated from the coherence function.

There is also a multi-dimensional version of this criterion using singular value decomposition of the matrix of transfer functions from the various sources of vibration to each sensor. The singular values represent normalized gains of the inverse (matrix) filter at each frequency. A general criterion for the extreme values of singular values based on the coherence function can be developed that is a direct analogy to the above two-port example [13].

The recovery of source waveforms, important for the diagnosis of impact events, depends on knowing the phase delay in the structural propagation. Gaining this knowledge is not easy, however, and the problem of designing inverse filters for mechanical systems forms a major part of our current research.

VI. Future developments

Noise control and noise reduction design have been and will continue to be major engineering activities, but the use of vibration and acoustical information for diagnostic purposes is growing and will continue to do so. The trends towards automated processes in manufacturing, intelligent machines, and the push for higher quality places a requirement for systems that monitor themselves, can identify faults, and suggest corrective actions. The sound and vibration produced by the operation of machines are not the only available signals for diagnostics, nor should these signals be used to the exclusion of temperature, fluid flow, currents and voltages, etc. Nevertheless, sound and vibration are intimately connected with the operations of mechanisms, and will have a central role in the development of diagnostic systems.

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