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MULTIPLE AND SINGLE INPUT TECHNIQUES APPLIED TO THE NOISE AND VIBRATION OF A MEDIUM POWER DIESEL ENGINE

P.R. Wagstaff, M. Taghavi Nejad, G. Marquette, J.F. de Belleval

Universite de Technologie de Compiegne - France

INTRODUCTION

The periodic nature of the sources of noise and vibration in an internal combustion engine creates a number of problems when the relative importance of the contribution of each source to the noise or vibration is required. Classical methods of signal processing yield results that can overestimate the contributions from an individual source because of the high degree of coherence existing between most of the sources.

Methods of treating the problem of multiple partially coherent sources have existed for some time and were first applied to the Diesel Engine by Chung et al. [1] in 1973. After a short period of interest they have virtually creased to be applied to this type of problem because of the generally unsatisfactory results obtained. The simplifications and approximations requiered to obtain results that match with physical reality have limited the utility of the final result.

This paper describes the application of these techniques to a medium power diesel engine and the ways that have been found of improving the accuracy of the results.

NOISE SOURCES IN A DIESEL ENGINE

Because of the high frequency content in the spectrum of the cylinder pressure variations in a diesel engine the noise problem is much more acute than for a petrol engine. This difference is caused by the rapid rise in pressure during combustion and is the most obvious noise source to consider. The effects of piston slap are also an important possible source because of the high levels of cylinder pressure around top dead centre. In both cases the spectra of these sources will be almost entirely composed of harmonics of the rotational speed of the engine with fixed phase relationships between each cylinder. For the lower frequency range this leads to a set of entirely deterministic periodic sources which may be treated as an ensemble rather than individually [2]. For the higher frequency range the harmonic components diminish and the random components of the sources become more important. Multiple input techniques may then be applied to the problem. Other sources may also be important and will also be partially coherent with the sources mentioned, but it is desirable to limit the analysis to as small a number of sources as possible. For this reason the first measurements made in this investigation were limited to the cylinder pressure sources, and three microphones to measure the radiated noise. A V12 turbo charged direct-injection engine manufactured by the S.A.C.M. developing 1200kw at 1500 R.P.M. was used for the measurements. In order to limit the number of sources, six of the pistons were removed and the engine ran on the remaining six cylinders.

PRINCIPLES OF THE METHOD OF ANALYSIS

A system with a number of different sources may be analyzed by considering the

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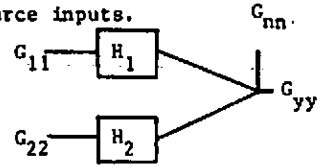
contributions of each source to the measured cross spectrum between a source and the out put.

For a system with two source inputs.



G_{11}, G_{22}, G_{yy} and G_{nn}, are the autospectral densities of input 1, input 2, the output and the measurement noise respectively and H_1 and H_2 are the true transfer functions between the first and second inputs and the output. In the case where the two sources are completely independent, the cross spectra between the two inputs and the output are gyven by.

$$G_{1y} = H_1 G_{11} \tag{1}$$

$$G_{2y} = H_2 G_{22} \tag{2}$$

when these two sources are partially coherent the equations become.

$$G_{1y} = H_1 G_{11} + H_2 G_{12} \tag{3}$$

$$G_{2y} = H_1 G_{21} + H_2 G_{22} \tag{4}$$

For the general case of n inputs

$$G_{iy} = \sum_{j=1}^{n} H_j G_{ij} \qquad i = 1,2 \ldots n \tag{5}$$

The unknowns are H_1 H_n and the equations may then be solved from the measured values of cross and auto spectra by normal matrix methods. A more interesting approach has been proposed [3] which gives greater physical insight into the characterities of the system. The parts of the systeme coherent with the first input are removed from all the other spectra thus producing a set of conditioned spectra only dependent on the remaining inputs. The effects of the other inputs are removed one by one until the last set of spectra contains only those parts of the signal that are independent of all the inputs except the last. This last system is then easily resolved.

In the case of the system with two inputs given above :

$$H_2 = \frac{G_{11}G_{2y} - G_{21}G_{1y}}{G_{11}G_{22} - G_{12}^{\,2}} \tag{6}$$

The conditioned spectra for the second input with the effects of the first removed are given by

$$G_{2y.1} = G_{2y} - \frac{G_{21}}{G_{11}} G_{1y} \tag{7}$$

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$$G_{22.1} = G_{22} - \frac{(G_{12})^2}{G_{11}} = G_{22}\ (1-\gamma^2_{12}) \tag{8}$$

Comparison with the expression for H_2 shows that

$$H_2 = \frac{G_{2y.1}}{G_{22.1}}, \tag{9}$$

This approach is particularly useful in defining significant quantities such as partial and multiple coherences and coherent output powers in physical terms. A full discussion is found in [3].

APPLICATION OF THE METHOD TO A DIESEL ENGINE

Initially the major problem was felt to be the high coherence between the input sources due to the periodic nature of the signals. The method of successively eliminating the effects of each input shows clearly the importance of high values of coherence between the inputs because as the coherence tends to unity the value of $G_{22.1}$ in equation (9) tends to zero. Therefore H_2 approaches infinity for very small errors of measurement in the spectra, when the value of γ^2_{12} is close to unity.

Elimination of the coherent parts of the signal eliminates virtually all the periodic components and leaves a small residue which is due to the variations in the combustion process for each cylinder. Any kind of synchronization of the acquisition of the spectra with the engine rotation increases the importance of the periodic components, so the spectra were initially calculated by continuous acquisition without any synchronization. The pressure and microphone signals were recorded directly on tape and then processed using a Nicolet 660A dual channel analyser linked to a PDP 11/23 computer, the cross and auto spectra being calculated by making sequential acquisitions two channels at a time.

Using resolutions of between 2.5Hz and 20Hz and frequency ranges from 0 to between 1000Hz and 10000Hz it proved impossible to obtain consistent results for the transfer functions of each cylinder even through the global result was reasonable. This was principally due to small variations in the cross spectra and residual spectra which greatly affected the end result even when the number of averages was increased.

By simulating a system with three real cylinder pressure signals played back through a block of attenuators and summation amplifiers it was discovered the method failed to correctly measure the transfer function at low frequencies because of the periodic components and at higher frequencies the results were simular to those obtained using a single input analysis for each pressure signal. When the coherence between the sources is examined it is easy to see the reasons for the problem, a very high level of coherence between the sources below 2000Hz which drops to a low level almost immediately for the higher frequencies. Figure 1 shows the coherence between two cylinder pressure signals for the frequency range 0 - 5KHz with a resolution of 10Hz. The engine speed in this case was 600 r.p.m.

METHODS OF IMPROVING THE RESULTS

With this relatively simple simulated system it is possible to reduce the coherence between the signals by "windowing" the date around the chosen source input signal providing that the signals are impulsive. If the response of the real system is of short duration compared with the time between successive input impulsions it is possible to analyse the response of a multiple input system using simple transient analysis and windowing in on the impulsions of the chosen input signal. When the pressure signals of a diesel engine are filtered to reduce the low frequency content the only part of the signal that remains is an impulsion of short duration at the moment of combustion (Figure 2). By triggering the acquisition from these impulsions the response of the system can be identified if the time window of the response signal contains uniquely the vibrations or noise generated by this input. At low engine speeds the impulsions are widely spaced and this condition can perhaps be met, but at high speeds this is no longer the case. The technique adopted to overcome this problem was to use the multiple input technique for three inputs only and calculate the response for a particular cylinder by including the cylinders that fire immediately before and immediately after it, in order to eliminate their effects. At the same time the acquisitions were carried out on the four channels, the three inputs and the output at the same time, to limit the errors caused by the small variations in the spectra using the sequential acquisition technique.

RESULTS

Figure 3 shows the results obtained on the simulated system at 600 r.p.m., firstly using the multiple input technique with each of the three cylinder explosions within the data window, and then using the single input analysis and the same data window. The modulus of the transfer function is a known constant value and the result using the multiple input technique yields the correct result. The single input technique shows the expected variations below 2000Hz because of the high inter-source coherence, but for higher frequencies the results are relatively good because of the lower coherence between the inputs at these frequencies.

This approach was applied to three cylinder pressure signals to calculate their contribution to the acceleration at a point on the engine block, again at a speed of 600 r.p.m. Figure 4 shows the result for the modulus of the transfer function between cylinder number 3 and the acceleration, firstly calculated using the multiple input technique, and then calculated by the single input technique. In this case the results are surprisingly close together, but the reduced variations of the multiple input result at low frequencies would lead to the conclusion that the errors have been reduced by this technique.

The multiple coherence between the three cylinders and the vibrations has well defined maxima where the transfer function has the least statistical errors. Figure (5). The high values of multiple coherence in these frequency ranges indicate that the model system represents fairly closely the true system characteristics. This is further underlined in Figure (6) which compares the coherent power due to these three inputs with the power spectrum of the accelerometer vibration.

When the same technique is applied to the noise measured by a microphone at 1m. from the block the results are less satisfying (Figure 7). The transfer function measured by the multiple input technique (upper curve) does not appear to be an improvement on the single input method. The two results are similar for the higher frequency range but have similar suspect variations at low frequency. The multiple coherence for the three cylinder pressures and the microphone signal shows that there are many low frequency components that are not included in the model (Figure 8).

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CONCLUSIONS

It is perhaps not surprising that the microphone gives inferior results to the accelerometer in view of the greater chances of influence by other external noise sources and the longer persistance of the noise due to the propagation delay and reflections in the test cell. The windowing technique does tend to reduce the coherence between the sources and the ouput noise in this case.

The final aim of this investigation is to relate the vibration and noise to the individual possible sources in order to understand the mechanisms involved. The most difficult problem to solve is that of finding criteria to indicate when the calculated result is correct. The criterion that this investigation will try and exploit is the agreement between the results of single input and multiple input methods at low speeds which can then justify the use of the multiple input methods at higher speeds where windowing is not sufficient to separate the inputs and responses. It is felt that the concentration on the cylinder pressures as sources is justified by the results obtained and that the phase variations caused by the natural variations in combustion event timing may be sufficient to render the piston slap incoherent with the cylinder pressures at higher frequencies.

REFERENCES

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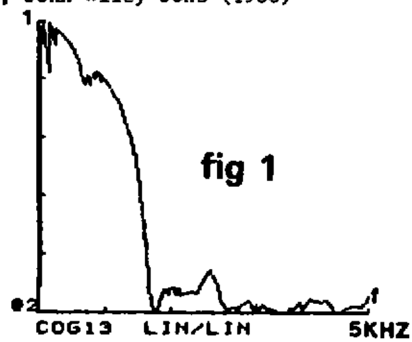

fig 1

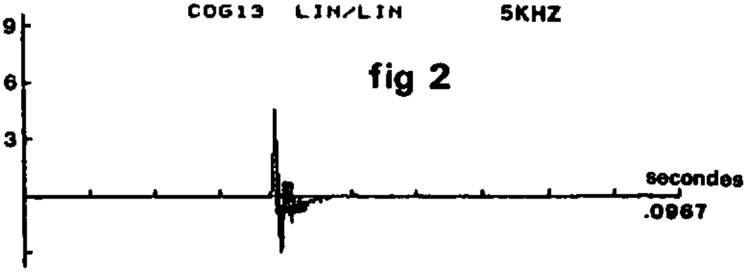

fig 2

MULTIPLE AND SINGLE INPUT TECHNIQUES APPLIED TO THE NOISE AND VIBRATION OF A MEDIUM POWER DIESEL ENGINE

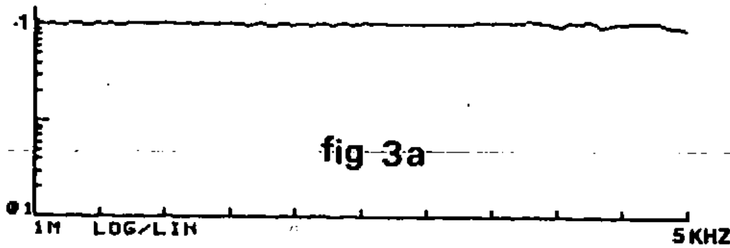

fig 3a

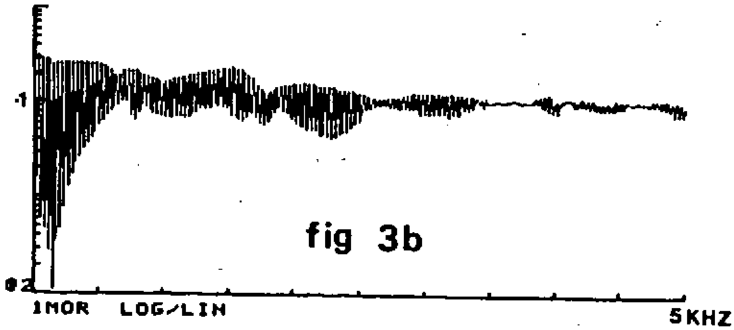

fig 3b

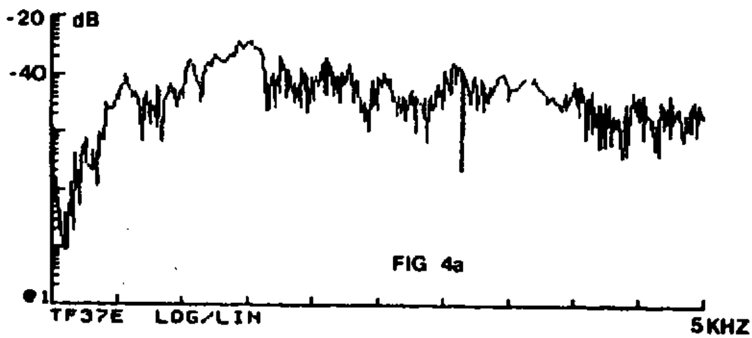

FIG 4a

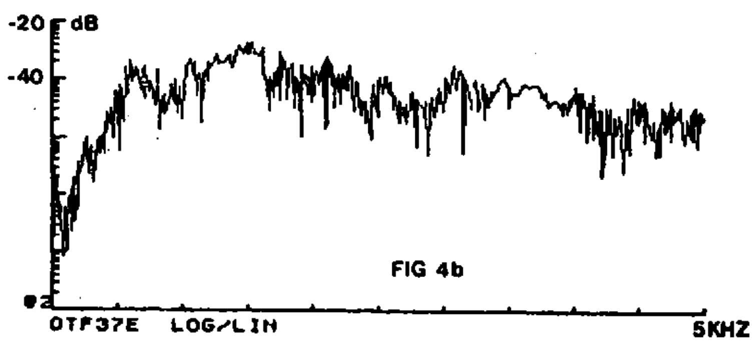

FIG 4b

MULTIPLE AND SINGLE INPUT TECHNIQUES APPLIED TO THE NOISE AND VIBRATION OF A MEDIUM POWER DIESEL ENGINE

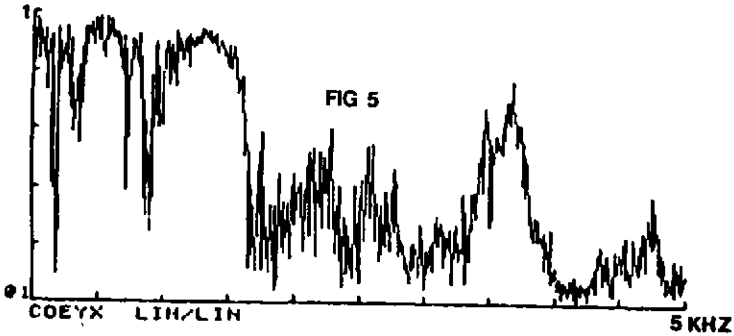

FIG 5

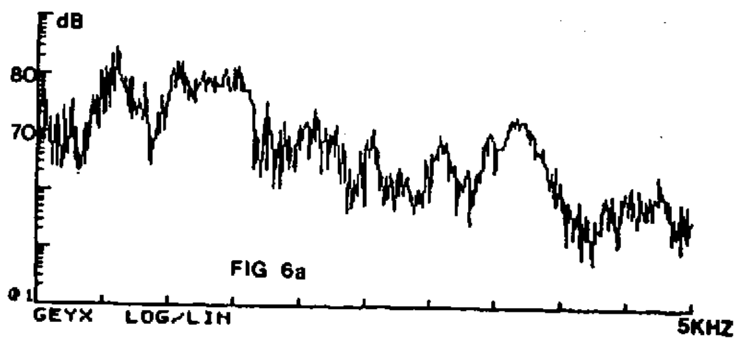

FIG 6a

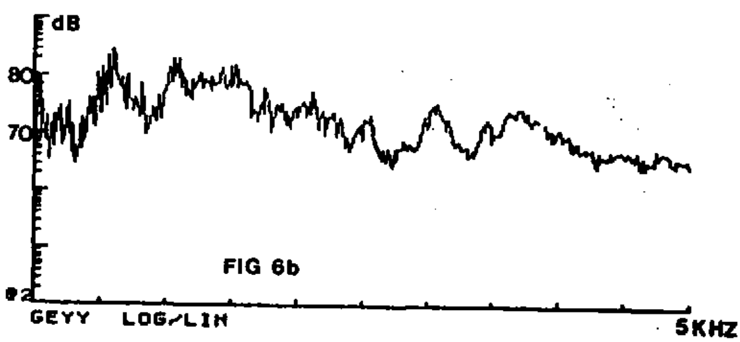

FIG 6b

MULTIPLE AND SINGLE INPUT TECHNIQUES APPLIED TO THE NOISE AND VIBRATION OF A MEDIUM POWER DIESEL ENGINE

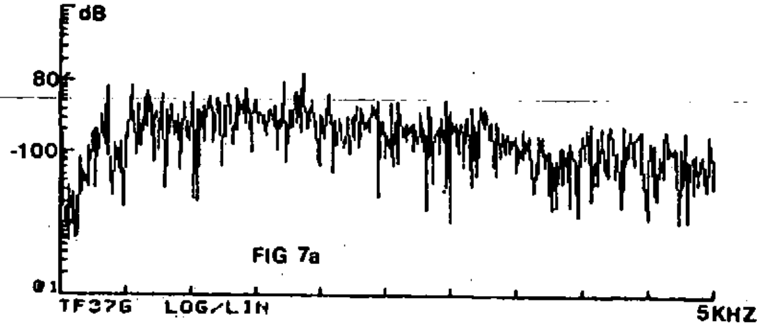

FIG 7a

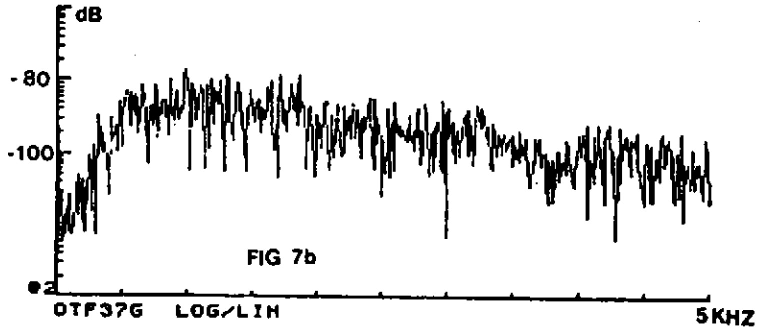

FIG 7b

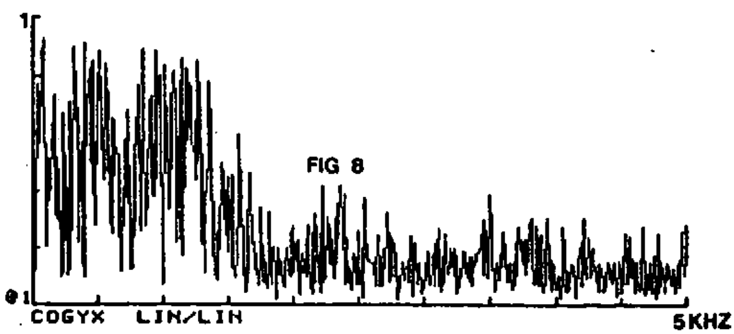

FIG 8