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INDIRECT RECONSTRUCTION OF IC ENGINE PRESSURE TRACE THROUGH STRUCTURAL VIBRATION INVERSE FILTERING

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ABSTRACT
This paper addresses the feasibility of reconstructing the pressure trace in IC engine from non-intrusive structural vibration measurements, by means of an inverse periodically time-varying filter. Therefore, the deconvolution problem is first formulated in a signal extraction framework and demonstration is made of the optimality of the proposed filter. Then, a solution for its implementation is proposed, based on the assumption of cycloergodicity. Finally, applications are made to real vibration signals issued from a diesel engine. Successes and limitations of the method are discussed in light of these results.

1 - INTRODUCTION
The cylinder pressure trace in IC engines is recognized to be an indicator of value, most often to be used for controlling a set of operating parameters, but for diagnosis purposes as well. This paper is dedicated to the latter issue and addresses the feasibility of reconstructing the pressure trace from non-intrusive vibration measurements. As a matter of fact, direct measurement of the pressure trace with a pressure transducer is hardly tractable in practice, as it usually requires to dismantle or to drill some parts of the engine, especially for diesel engines. Therefore, any alternative option is of interest. One option is concerned with the measurement of the structural vibrations on the block engine, which are supposed to result from the pressure forces. Appropriate processing of these has been proposed in the literature to recover the pressure trace partially or fully [1-3]. However, these methods as most deconvolution issues are known to be ill-posed and delicate to implement. According to the essentially high-pass nature of vibration signals, reconstruction of the slow fluctuations in the pressure trace is often found to be difficult. In addition, the structural vibration signals are often contaminated with some extraneous sources, such as the very noisy piston slap in diesel engines. This paper focuses on these issues and proposes to reconstruct the overall pressure trace from noisy vibrations by making use of redundant spectral information induced by the non-stationarity (cyclostationarity) of the signals. Indeed, we show how to extract the useful information from linear periodically time-varying filtering.

2 - MATHEMATICAL FORMULATION
Due to lack of place, it is not possible here to first investigate the problem from a mechanical viewpoint. However, one just need to say that simple mechanical considerations can demonstrate the periodic time dependence of the system relating the pressure forces $p(t)$ to the vibrations $y(t)$ on the block engine. Accordingly, and for a (almost) constant operating speed, the input/output relationship can be expressed as,

$$y(t) = \int_{-\infty}^{+\infty} h(t,\tau)\, p(\tau)\, d\tau \tag{1}$$

where the Green's function $h(t,\tau)$ is defined as the system response at time t to an impulse applied at time τ and is periodic with the thermodynamical cycle T such that $h(t,\tau) = h(t+T,\tau+T)$. When working with digital signal, relationship (1) is recast into a matrix form. For instance, in the frequency domain, $\mathbf{Y}=\mathbf{HP}$, where $\mathbf{Y}_i$ and $\mathbf{P}_i$ are vectors containing the frequency samples of the discrete Fourier transform of the digitized $y(t)$ and $p(t)$, and where the matrix $[\mathbf{H}]_{kl}$ contains the samples of the double discrete Fourier transform of the Green's function. Let us now consider the problem of extracting the signal $\mathbf{P}$ from structural vibration measurements. In practice, the vibration signal $\mathbf{Y}$ will be further corrupted by the piston slap noise $\mathbf{N}$, which occurs at the top dead center (TDC) almost at the same time as the combustion does. Unfortunately, its effect can account up to 50% of the global vibration energy in the measured signal, say $\mathbf{Z}=\mathbf{Y}+\mathbf{N}$, that is a signal to noise ratio as poor as 0 dB at TDC [4]. Therefore, the issue is to find a filter $\mathbf{G}$ which, when applied on $\mathbf{Z}$, both removes the effect of $\mathbf{H}$ and attenuates that of the noise $\mathbf{N}$ so that $\mathbf{P}$ can be recovered as best as possible. Determination of the optimal (Wiener) filter $\mathbf{G}$ is achieved by classical minimization of the mean square error. By denoting $\mathbf{S}_{UV}$ the spectral correlation matrix $E\mathbf{V}\mathbf{U}^H$, this yields

$$\mathbf{G}_o=\mathbf{S}_{ZP}\mathbf{S}_{ZZ}^{-1}=\mathbf{S}_{YP}\mathbf{H}^H\left[\mathbf{H}\mathbf{S}_{YY}\mathbf{H}^H+\mathbf{S}_{NN}\right]^{-1} \tag{2}$$

where the second equality stands whenever $\mathbf{Y}$ and $\mathbf{N}$ are uncorrelated. Inspection of formula (2) enables two main statements:

- As long as the spectral correlations $\mathbf{S}_{ZP}$ and $\mathbf{S}_{ZZ}$ are not diagonal (i.e. signal $p(t)$ and $y(t)$ must be jointly cyclostationary), the optimal inverse filter $\mathbf{G}_o$ is found to be periodically time-varying, just as the direct filter $\mathbf{H}$. Then $\mathbf{P}_{est}=\mathbf{G}_o\mathbf{Z}$ yields an estimate of $\mathbf{P}$. This matrix equation simply means that the harmonic of $p(t)$ at a given frequency will be reconstructed from a weighted average of the harmonics of $y(t)$ spanning over all the frequency range of interest. Accordingly, it is hoped that the low pass components of the pressure signal could be reconstructed from the high pass components of the vibration signal, thus circumventing the ill-posed deconvolution issue.

- At these couples of frequency bins (k,l) where the corrupting noise is insignificant, the optimal inverse filter $[\mathbf{G}_o]_{kl}$ tends to be equal to the ideal equalizer $[\mathbf{H}^{-1}]_{kl}$. On the contrary, at these couples of frequency bins where the noise is predominant, $[\mathbf{G}_o]_{kl}$ tends to be an ideal rejector, i.e. a filter with null gain. Because of the bifrequency nature of the filter, higher rejection is achieved than in the (monofrequency) time-invariant case: noise can be attenuated, even if its time or frequency spans (but not both) are overlapping with those of the pressure forces. As a consequence of this time-varying rejection ability, we actually noticed that there is virtually no need to window the vibration signal before processing it, as it is usually done in order to separate out the combustion signature waveform from other neighboring sources.

3 - PRACTICAL IMPLEMENTATION

3.1 - Assumption of cycloergodicity

The identification of the optimal inverse filter through formula (2) is easily amenable under the assumption of cycloergodicity. Basically speaking, this means replacing ensemble averaging by cycle averaging so that estimation of the expectation operator E. is possible. Application of the material introduced in the previous section tightly relies on this mathematical trick. Fortunately, the assumption of cycloergodicity seems to be a reasonable one, as long as the engine is running with (almost) constant speed.

3.2 - Tuning the number of degrees of freedom

One drawback of the periodically time-varying filter compared to its time-invariant counterpart is an increase in the number of parameters, since we are now dealing with a matrix instead of a vector. From an estimation viewpoint, this situation should be avoided as it jeopardizes the statistical significance of the estimates. In the sequel, we show that drastic reduction in the number of degrees of freedom (d.o.f) can be achieved by filtering out the smallest eigenvalues of the $\mathbf{S}_{ZZ}$ spectral correlation matrix in (2) before inverting it.

4 - APPLICATIONS

This section presents some results of experiments run on a test ring at the **University of New South Wales** (Australia). The engine under test was a 4 cylinder 4-stroke diesel Perkins, on which the first cylinder was equipped with a pressure transducer and two accelerometers on its head bolts. A sampling frequency of 11.9 kHz was chosen and a number of data recordings were performed for different engine

speeds and load torques, along with a one pulse per revolution signal. This enabled post-synchronization of the data with respect to the TDC, so that the pressure and the accelerometric signals were coded with 512 points on each cycle, for a total of several hundred cycles. For each tested speed, the data were finally divided into a training set and a test set. The training set was used to identify the optimal inverse filter $\mathbf{G}_o$ between the first accelerometric signal and $p(t)$, whereas the test set was used to estimate the induced normalized mean square error (NMSE) between the reconstructed pressure trace and the true measured one.
Figure (1) shows the multiple coherence function given by $\gamma^2_{pz} = \mathrm{diag}\left(\mathbf{S}_{PZ}\mathbf{S}_{ZZ}^{-1}\mathbf{S}_{ZP}\right)/\mathrm{diag}\left(\mathbf{S}_{PP}\right)$ w.r.t to the number d of eigenvalues retained when inverting the $\mathbf{S}_{ZZ}$ matrix. d=1 can be compared with the identification of a time-invariant filter. One can then appreciate the fast improvement in the coherence level when increasing d, except in the [100 Hz;300 Hz] frequency band where it remained unfortunately quite low. This could be either due to the inability of the inverse filter to model the true input/output relationship or to excessive corrupting noise in this frequency band.

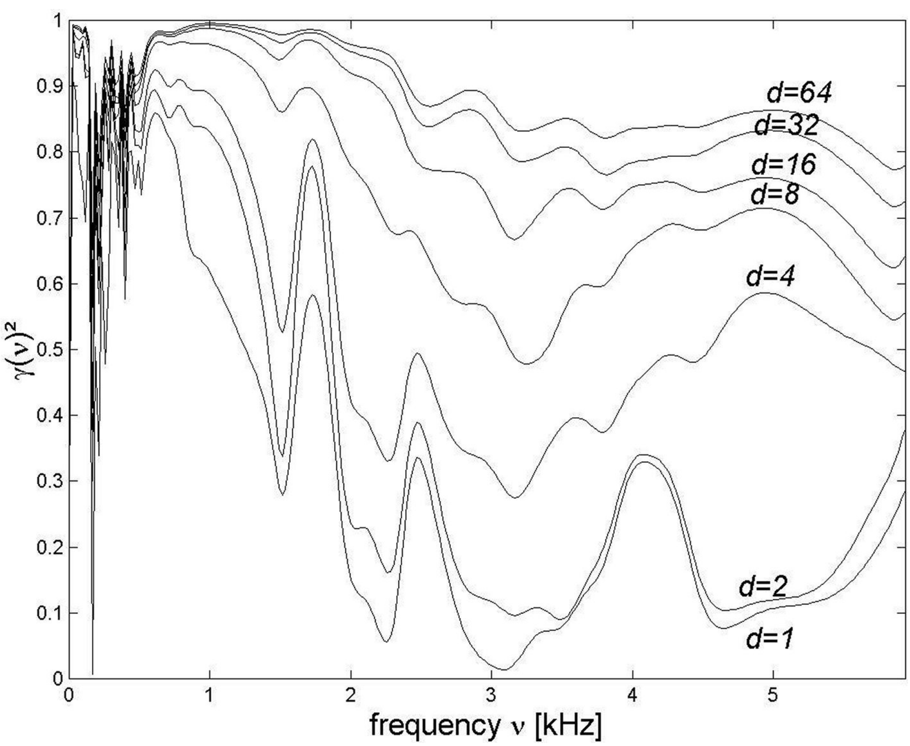

Figure 1: Multiple coherence functions w.r.t d.

Figure (2) displays the NMSE versus to the number d of d.o.f. As expected, the NMSE on the training set decreased monotonically with d, which agreed with some overfitting of the model. Besides, the NMSE on the test set passed through a first minimum for d=16 and did not overrun it before d reached unacceptable high values (d>75). Consequently, the "optimal" value d_{opt}=16 was selected. This gave a very satisfying compression ratio of 96.88% for the number of d.o.f. Therefore, the matrix filter $\mathbf{G}_o$ may be viewed as 16 time-invariant filters in parallel, instead of 512 as originally stated.
Performances of the inverse filter to reconstruct the pressure traces are shown in figures (3) and (4), for two different tested torques and a selected speed of 1200 rpm. Figure (3) is an example of a good reconstruction, and figure (4) of a poorer one. In both figures, the pressure traces were recovered form accelerometric signals drawn from the test set. The upper pictures relate to sensor N°1 that was actually used to identify $\mathbf{G}_o$, whereas the lower pictures relate to sensor N°2, which was located 5 cm away from N°1.
These results call for some comments:

- The overall shape of the pressure trace was well recovered, and there were no spurious oscillations induced by the deconvolution process, as it is sometimes the case when time-invariant methods are applied to transient signals.
- The recovered pressure traces were almost identical for the two sensors, thus demonstrating the

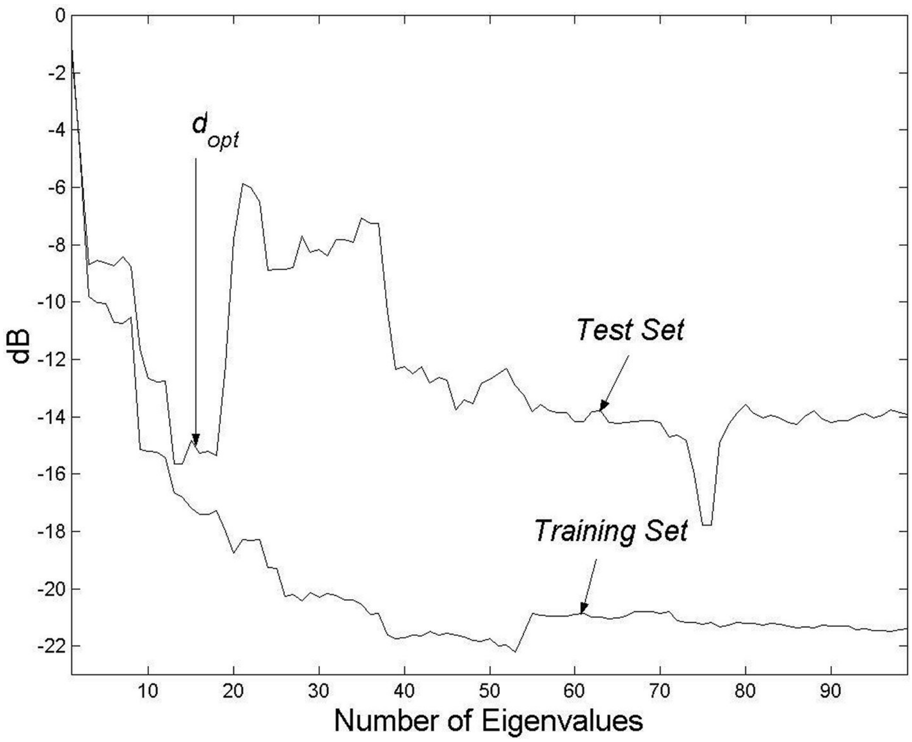

Figure 2: NMSE errors vs d.

feasibility of using the estimated $\mathbf{G}_o$ to deconvolve accelerometric signals issued from other sensors, as long as their transfer functions $\mathbf{H}$ are not too different.

- Reconstruction of the low frequencies in the pressure trace was not always as good as expected, and it seemed that $p(t)$ was only recovered within an unknown scale factor. Actually this uncertainty tallied with the information obtained from the multiple coherence function in figure (1), stating that poor input/output relationship was found in the [100 Hz; 300 Hz] frequency band. This result could be case-related and may not apply in general to other tested engines.

- It can be seen from figure (4) that reconstruction was especially difficult when the energy of the combustion pulse was low. Here, the issue concerned with ill-posed deconvolution methods emerged again. As a matter of fact, we were able to observe that the weaker the combustion pulse, the poorer the deconvolution performances. These limitations might be virtually inherent to structural vibration based methods.

5 - CONCLUSION

This paper addressed the feasibility of reconstructing the cylinder pressure trace of IC engines trough inverse filtering of noisy structural vibration signals. It was shown that the optimal inverse filter is periodically time-varying, and has the potential to reconstruct low frequency harmonics of the pressure forces from harmonics of the accelerometric signal spanning over all the frequency range of interest. Besides, it has the potential to efficiently reject corrupting noise, such as piston slap. Effectiveness and limitations of the method were discussed on real data from a diesel Perkins engine.

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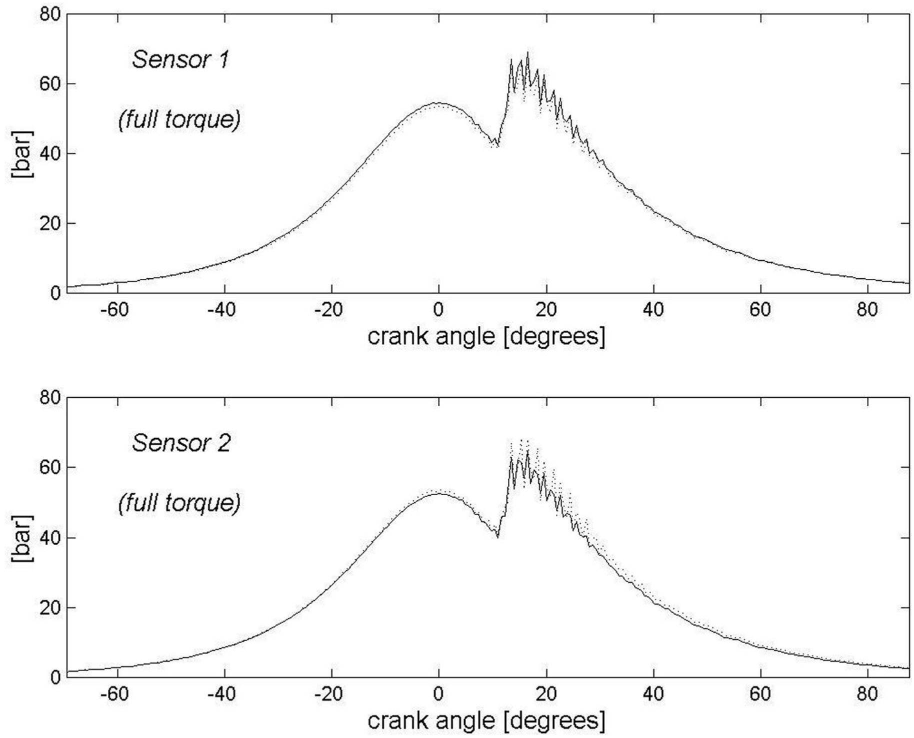

Figure 3: Reconstructed (continuous line) and measured (dashed line) $p(t)$ $-$ full torque.

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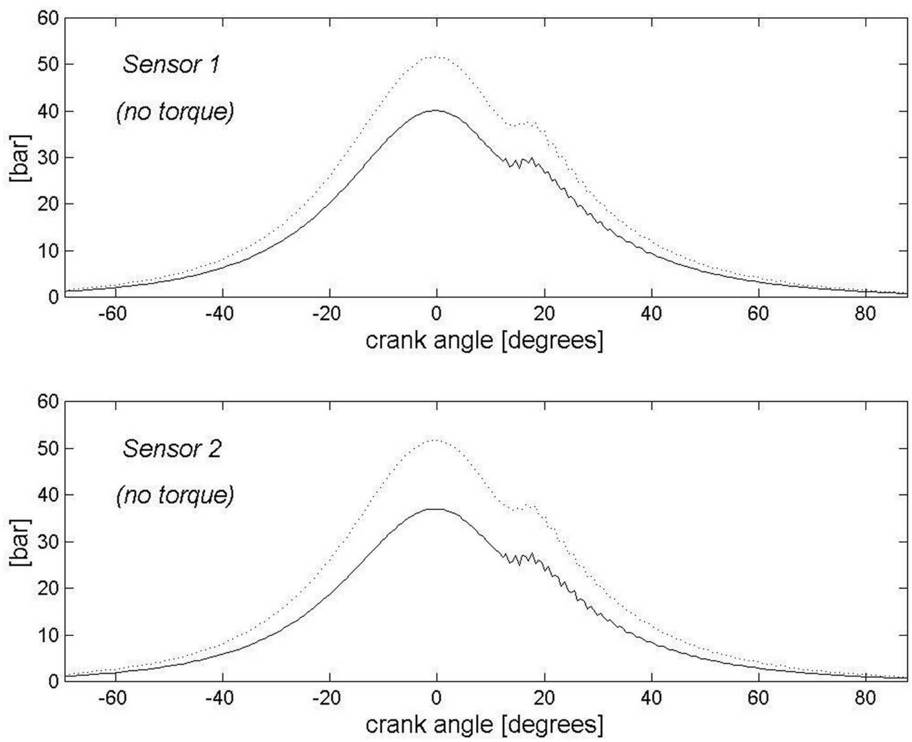

Figure 4: Reconstructed (continuous line) and measured (dashed line) $p(t)$ − no torque.