Removal of shaft speed related components from the response signals of a machine with varying speed prior to Operational Modal Analysis

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ABSTRACT

It is an advantage to remove discrete frequency components from response vibration signals before carrying out operational modal analysis (OMA), because they tend to disrupt the operation of normal OMA algorithms. The removal of such components can be achieved by carrying out order tracking, to remove the effects of speed variations by resampling with a fixed number of samples per period of the frequencies to be removed, so that they are in discrete lines in the order spectrum, and can then in principle be removed by techniques designed for constant speed machines. If the speed variations are greater than 1% or so, the spectrum of the order tracked signals is no longer a frequency spectrum, so modal properties, which are related to frequency, can no longer be obtained by OMA. This paper introduces a method where signals are transformed into the order domain, and after the removal of shaft speed related components are transformed back to the time domain to allow normal OMA to be applied. The method is demonstrated using signals from a gearbox casing excited (via a shaker) with a varying frequency signal containing 22 harmonics corresponding to speed variations of ±15%.

Keywords: Operational modal analysis, Order removal, Variable speed I-INCE Classification of Subjects Number(s): 74.9

1. INTRODUCTION

Modal analysis is a very powerful way of describing the dynamic properties of a structure or machine in terms of its natural frequencies (and associated damping) and corresponding deformation mode shapes. With a scaled modal model it is possible to estimate transfer functions from any source to any measurement point, and thus in principle predict the vibration response to a prescribed set of excitation forces. Alternatively, for condition monitoring it is possible to relate measured responses to estimated forcing functions, to determine changes in the latter.

Analytical modal models are typically estimated from finite element (FE) models, but there can be quite large errors caused by poor modelling of joints etc, so it is desirable to update the analytical models from measured dynamic properties. In principle this requires the simultaneous measurement of both forces and responses, typically in the laboratory, but where the actual forces are different from those in operation. Thus, in recent years there has been considerable development of Operational Modal Analysis (OMA), where the modal properties are estimated from responses only, on the basis of certain assumptions, such as that the modes can be considered as coordinates, and thus responses will typically have maxima at the actual natural frequencies.

OMA generally assumes that the excitation is broadband, and often white (at least in the vicinity of the natural frequencies), but when the excitation contains discrete frequency components, such as harmonics of shaft speed, these tend to be treated by the software as modes with very low damping. A number of techniques have therefore been developed to remove discrete frequency components before further processing, and one way of doing this involves “order tracking”, the resampling of the signal from constant intervals in time to constant intervals in shaft rotation. This gives a fixed integer number of samples per revolution, and permits “time synchronous averaging” (TSA) whereby the periodic components are determined by averaging over many rotations, after which the (deterministic) part can

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be subtracted, leaving the response to broadband random excitation, and facilitating OMA. If the speed fluctuations are very small, the scaling from time to “periods” or rotations is a simple scaling factor, and the processed signals can be subjected to OMA directly. This was the case for example in Ref. (1), where the harmonics of rotor speed were removed from the response signals of a helicopter in steady flight, allowing OMA to be performed. If the speed varies somewhat more, however, the order axis is quite different from a frequency axis, and since natural frequencies are related to true frequency, and not order, it is necessary to reverse the order tracking operation back to the time domain before carrying out OMA on the signals with order related components removed.

This paper describes a method whereby signals from a machine with varying speed could have such discrete order-related components removed in the order domain, where they are uniformly spaced, and then transformed back to the time domain where OMA could be applied. The actual OMA has not yet been carried out, because of lack of time, but it is demonstrated that the resulting processed signals have frequency characteristics similar to those for an almost identical structure, much more so than the original measured response signals.

2. EXPERIMENTAL DATA

2.1 Test Object

Instead of an actual gearbox with varying speed, response signals were obtained from a gearbox casing, excited through a shaker with a “periodic” force signal containing 22 harmonics of a fundamental frequency. This has a mean of 76 Hz, but varies around this by ±15%, with a modulating frequency of 2 Hz (0.5s period). The total signal length was 2 mins (240 modulation periods). The higher harmonics had slowly decreasing amplitude given by $0.98^{(n-1)}$, where n is the harmonic order, so that the highest order had amplitude 0.98^{21} = 65.4% of that of the fundamental. The stated amplitude was that of the signal sent to the shaker, so that of the actual force would have been influenced by the response properties of the test object. The force was measured, so as to be able to carry out experimental modal analysis, but it was discovered that there was a fault with the force measurements, so that the experiment will have to be repeated later to obtain actual measured modes and compare them with the results of OMA. The measurement setup is shown in Figure 1.

In this paper only the signal pre-processing procedure is described in detail. Some comparison can be made with the results of an experimental modal analysis of the same casing (2) using hammer excitation, but the suspension was different so the results cannot be directly compared.

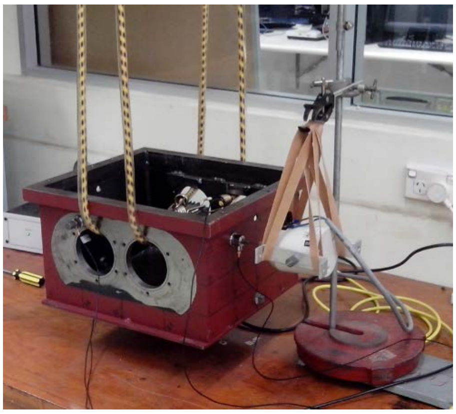

Figure 1 – Measurement setup for exciting the gearbox casing with a shaker

2.2 Input and Response Signals

The varying speed order related forcing function was made up of 22 cosines, so as to make the forcing function periodic impulsive. A short section is depicted in Figure 2(a), but it is too short to see the ±15% variation in period every 500ms. Figure 2(b) shows the corresponding spectrum up to the highest excitation frequency. White noise was added to this signal over the full valid frequency range (10 kHz, corresponding to sampling frequency 25 kHz). It is seen that the first order is separable in the spectrum, and this could thus be phase demodulated to obtain a time/phase map to allow resampling to the order domain (3).

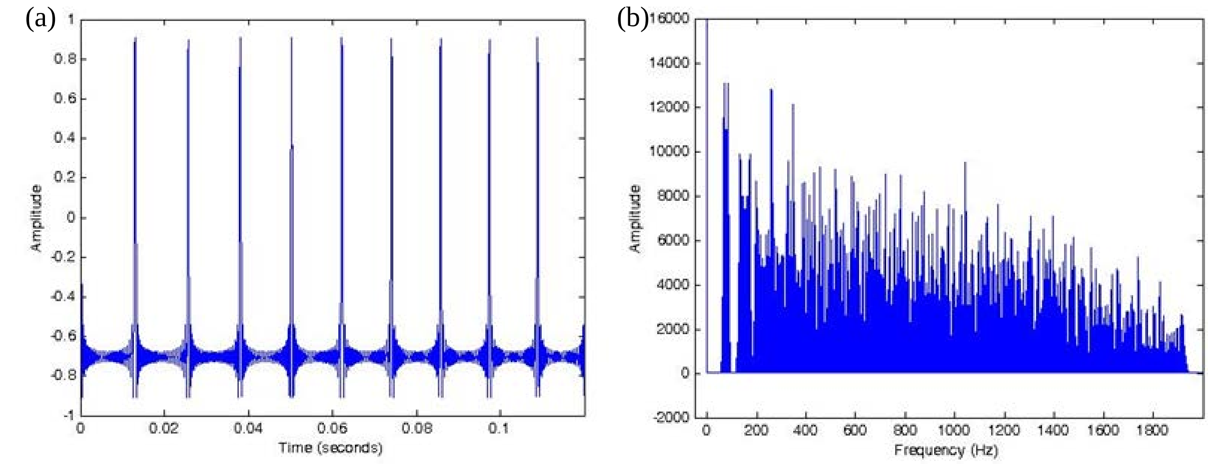

Figure 2 – (a) Section of input time signal (b) Spectrum of 22 orders

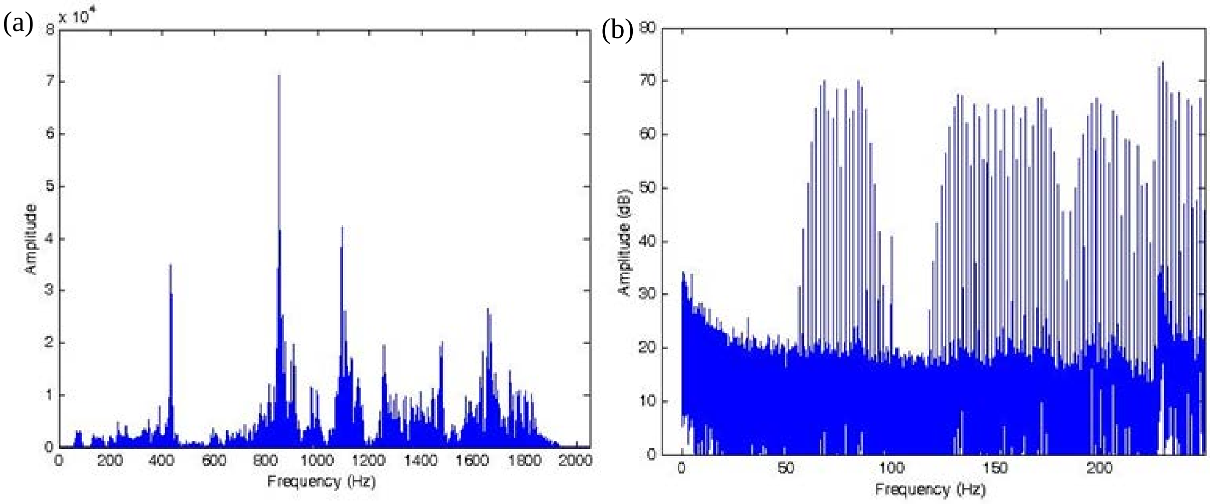

Figure 3 – Response spectra (a) Linear amplitude (b) dB amplitude, zoomed on lowest four orders

Figure 3 shows spectra of the response signals. Fig. 3(a) shows the spectrum on a linear amplitude scale, where the base noise level cannot be seen. Fig. 3(b) shows the lower frequency part of the spectrum on a dB scale, where the noise level can now be seen at about –50 dB. It is seen that the first order is still well separated from higher orders, so even the response signal could be used as a reference for the phase demodulation (3), and was in this case. Here, the modulation frequency is sinusoidal in the time domain, so the modulation sidebands (spaced at 2 Hz) are discrete and separated in this spectrum, but in the more general case of varying speed, the modulation sidebands would usually be smeared together.

3. REMOVAL OF ORDER RELATED COMPONENTS

3.1 Order Tracking

Order tracking was carried out by the phase demodulation based method described in detail in (3). In this procedure, a reference signal phase-locked to shaft speed is phase demodulated to obtain a map of phase vs time, uniformly sampled in time. This is then used to resample the signals at equal intervals of phase, so that one revolution of the reference shaft is always sampled with the same number of samples and starting at a given phase reference point (eg an upward moving zero crossing). In normal phase demodulation it is standard to remove the carrier frequency component (phase demodulation is defined as variation of phase around this carrier), and it is necessary to do that here as well, since the phase obtained by an inverse tangent operation is always in the range $\pm\pi$, and has to be “unwrapped” to a continuous function of time by removing jumps over 2π. This unwrapping usually requires that the slope in phase corresponding to any residual added frequency is minimized. It is also usually convenient to reduce the sampling frequency of the modulation signal at the same time, since the modulation frequencies in general are much lower than the carrier, but here the original sampling frequency should be retained, and the removed carrier frequency f_c (which is known exactly) should be re-added to the demodulated and unwrapped phase so as to obtain the correct phase vs time map.

The major advantage of the phase demodulation method is that as long as the modulation sidebands for the demodulated order do not overlap with those of higher orders (applicable here for the first harmonic) the true phase/time relationship can be obtained to any degree of resolution, simply by zero padding the spectrum of the reference signal around the Nyquist frequency so as to arbitrarily increase the sampling frequency. Windowing in the frequency domain like this corresponds to convolution in the time domain with a sinc(x) function, but since this is infinitely long it would have to be truncated, and would give unknown errors.

Once the times at which the resampling is to be carried out are known, it is usual for the signals to be resampled at those times using cubic spline interpolation. Note that the signals to be resampled must be appropriately oversampled in the time domain so that aliasing does not occur in the order domain. Since the maximum speed variation allowed by this method is 2:1 (from 2/3 to 4/3 of the carrier frequency, to avoid overlap of the sidebands of the second harmonic over those around the first harmonic) an expedient way of ensuring that there will be no aliasing, even at the lowest speed, is to oversample the signals by a factor of 2 before demodulation (3).

Figure 4 shows order spectra of the response signal, on both linear and dB amplitude scales, where it can be seen that the harmonic orders are now located basically in single spectral lines. This is not completely true, as even though the effects of frequency modulation have been removed, there is still some residual amplitude modulation. This is typically caused by the passage of strong forcing harmonics (such as gearmesh frequencies in a gearbox) through resonance frequencies as the speed varies. It means in fact that time synchronous averaging (TSA) of such signals does not necessarily give a physically meaningful result, since it will find the average amplitude over the whole record, and when this is repeated periodically and subtracted from the whole, the resulting residual signal will contain some deterministic as well as random information. This was not a problem in Ref.(1) since the speed was effectively constant.

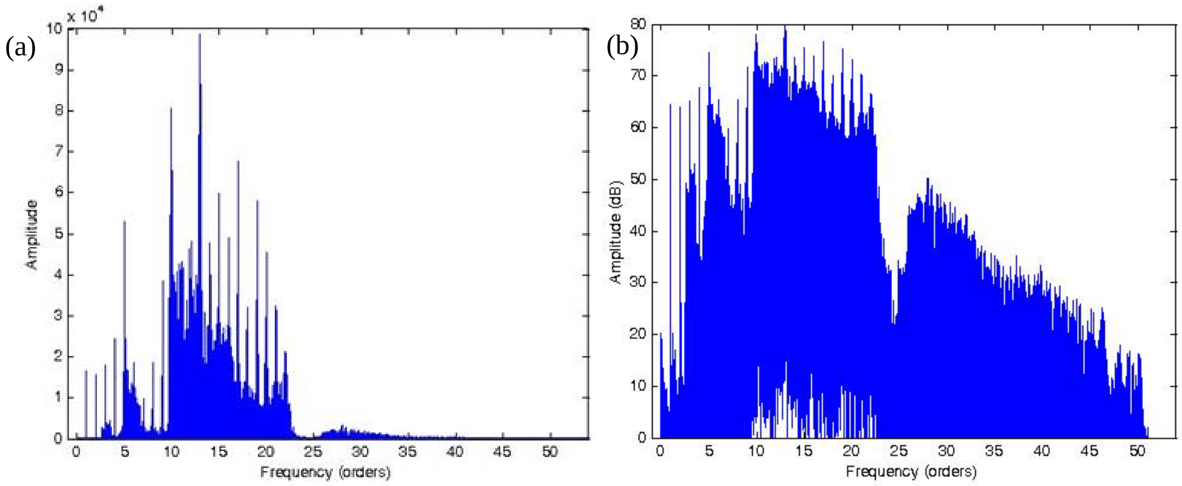

Figure 4 – Response spectra in order domain (a) Linear amplitude scale (b) dB amplitude scale

3.2 Removal of Discrete Harmonic Orders

Rather than attempting to remove the order information using TSA, it was decided to use the cepstral methods developed in Ref.(4) (for the same data as (1)), although modified in this case because of the much larger speed variation. The cepstrum is the inverse Fourier transform of the log spectrum, and so periodic structures in the spectrum are represented in the cestrum by a series of “rahmonics” with spacing equal to the reciprocal of the spacing of the harmonics. In fact, modulation sidebands are also equally spaced in the spectrum, and can be removed in the cepstrum even if they are not harmonics at the same time; something which cannot be done by TSA (5). Another advantage is the possibility to remove periodic structures in the spectrum even if they are not discrete frequencies. An example of this is given by blade pass frequencies in pumps, fans, turbines, where the connection between the blades and the casing is via a turbulent fluid, so that the higher order “harmonics” of the bladepass frequencies are not pure frequencies and tend to broaden slightly. TSA then tends to remove just the centre frequency in the broader peak, whereas the cepstrum method removes the whole structure (5).

In this case, an attempt was made to use just a “comb lifter” to remove the rahmonics corresponding to the fundamental periodicity of the order spectrum, as seen in Fig. 4. Figure 5(a) shows the cepstrum obtained by inverse transformation of the log spectrum of Fig. 4(b) (2-sided, including negative frequencies). Figure 5(b) shows the edited (liftered) cepstrum after removal of the main rahmonic family. Figure 5(c) shows a zoom of a low quefrency section of Fig. 5(b), indicating the removal of rahmonics by setting 7 lines to zero (centred on each rahmonic). Note that setting the cepstrum to zero automatically ensures that the resulting log spectrum has a smooth transition over the removed harmonics, since if the editing left notches in the log spectrum, these would also give a non-zero cepstrum component.

Incidentally, the type of cepstrum used here was the real cepstrum, where the editing modifies the log amplitude spectrum only, but this is then combined with the original phase of each record to regenerate time signals. This procedure is described in Refs.(4, 6). The so-called “complex cepstrum” can be reversed to time signals, but can only be calculated where the spectrum phase can be unwrapped, and this is not possible for stationary signals, as explained in (4, 6).

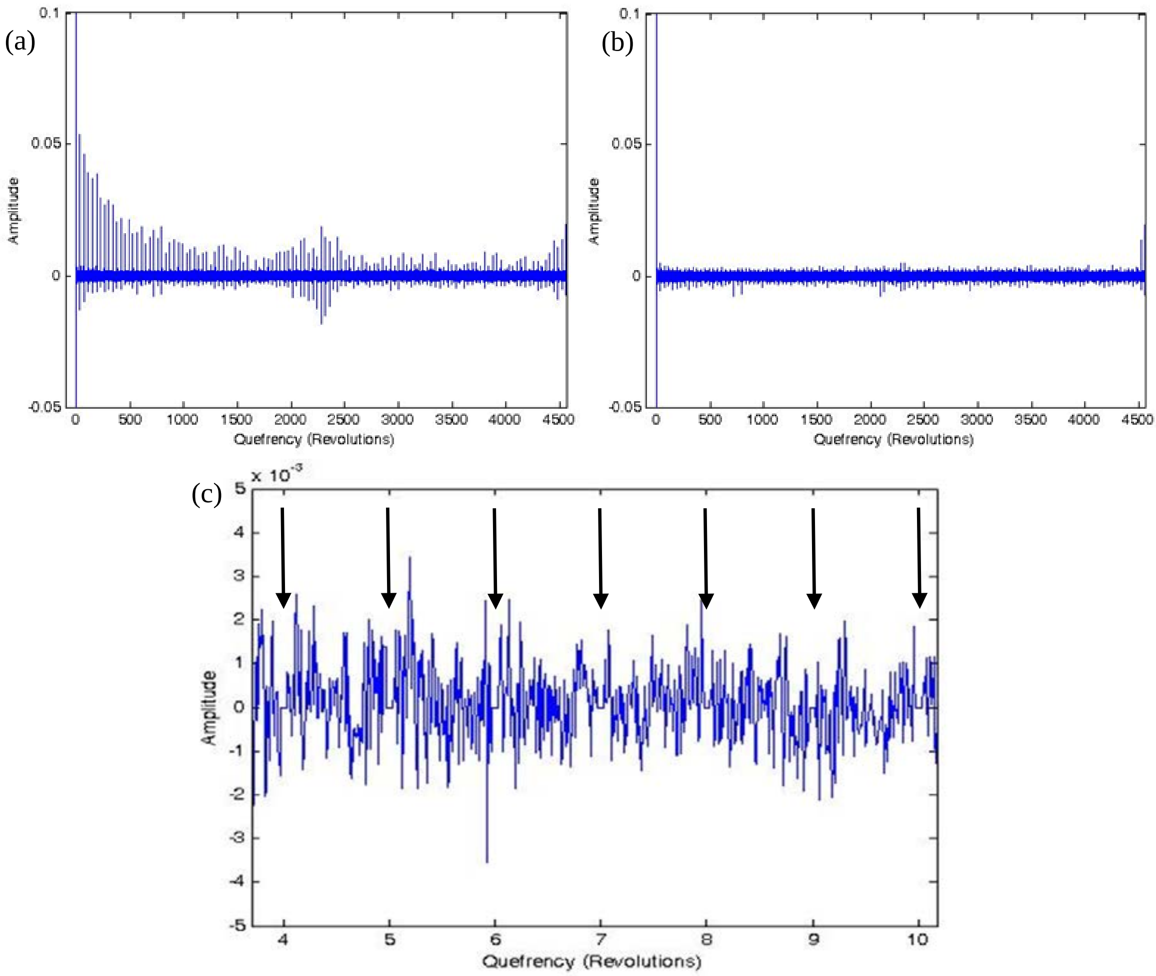

Figure 5 – Cepstrum of order spectrum (a) Original (b) Comb liftered at order rahmonics
(c) Zoom on low orders of (b)

Transforming back to the edited spectrum, as shown in Figure 6(a), shows that most of the periodic structure in the spectrum has been removed, but a zoom on the low orders in Fig. 6(b) (on dB scale) reveals that some components are still left, probably coming from the amplitude modulation which results from the ±15% frequency sweep. It was thus decided to apply an additional exponential lifter, as in (4), to remove such “high quefrency” disturbance, and emphasize the modal information at low quefrency. There is one difference with respect to (4), and that is that the exponential lifter does not directly correspond to damping, as it does when the quefrency axis is time rather than periods. In the

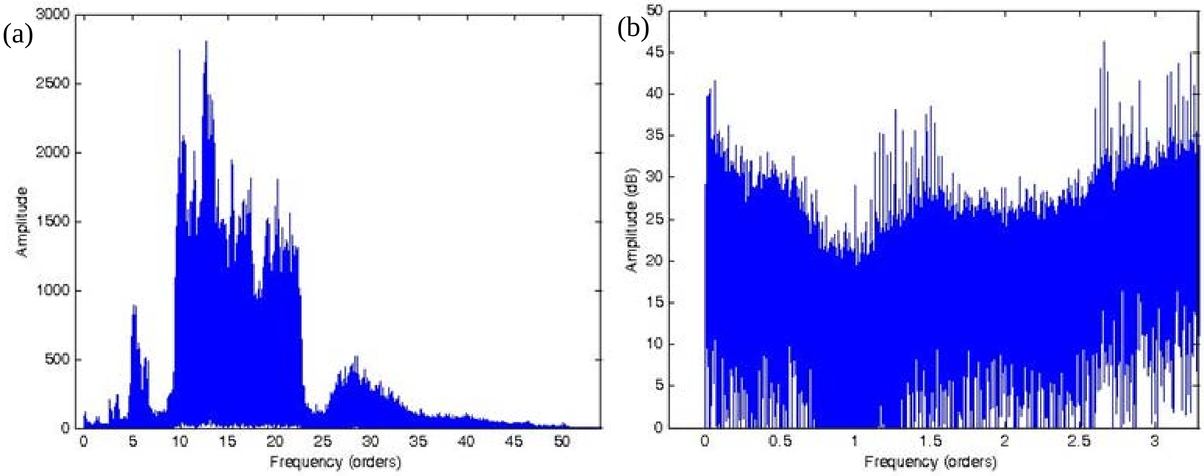

Figure 6 – (a) Edited spectrum (cf 3(a)) (b) Zoom on low orders (dB scale)

former case, the time constant of the exponential window corresponds to the decay of the additional damping added to each mode in the frequency response function (FRF), but when the speed is varying by ±15%, this would give a corresponding variation in the equivalent damping time constant. However, it was intended to apply a further lifter in the time domain, and as shown below this would then dominate the overall final damping. Note that since this time constant is known precisely, its effect can be subtracted from final OMA results, just as is done for exponential time windows applied to lightly damped responses in impact based experimental modal analysis.

Figure 7(a) shows the exponentially windowed version of the cepstrum of Fig. 5(b). The window had a time constant of 800 samples, so that it effectively removed periods > 5-10 revolutions. Figure 7(b) shows the equivalent response spectrum (not averaged), indicating that most information other than modal has been removed (cf Fig. 6(a)).

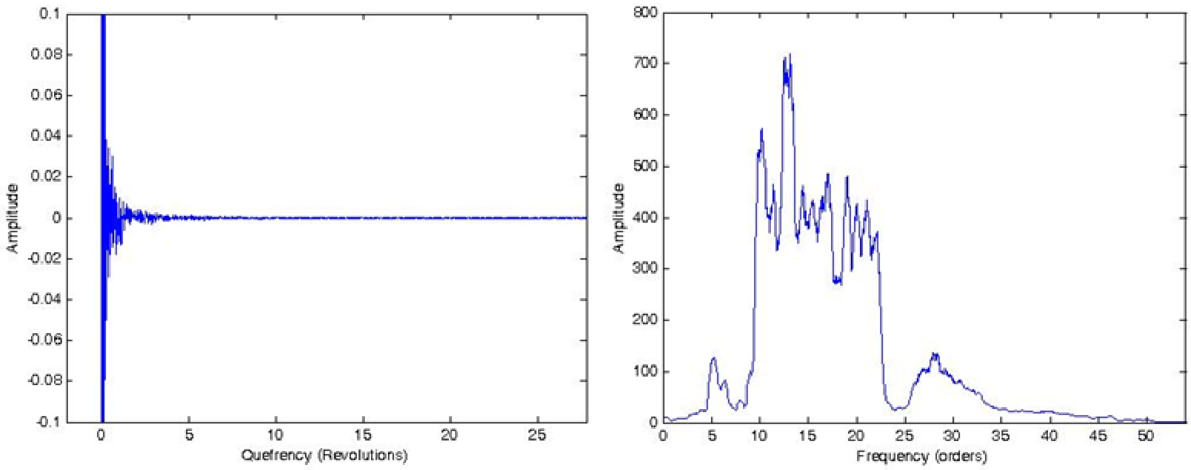

Figure 7 – (a) Exponentially windowed cepstrum (b) Corresponding liftered order spectrum

4. REVERSION TO TIME DOMAIN AND OMA

4.1 Reversion to Time Domain

Once the “time” records (in the order domain) have been reconstituted with the modified spectrum amplitudes, the same phase/time map as used to go from time to rotation angle can be used to reverse the operation and resample from uniform intervals in phase to uniform intervals in time again. When this was done in this case, the spectrum shown in Figure 8(a) resulted. Although all visible orders have been removed (cf Fig. 3) some residual components are still present, which are best seen in the corresponding cepstrum (time domain) of Fig. 8(b).

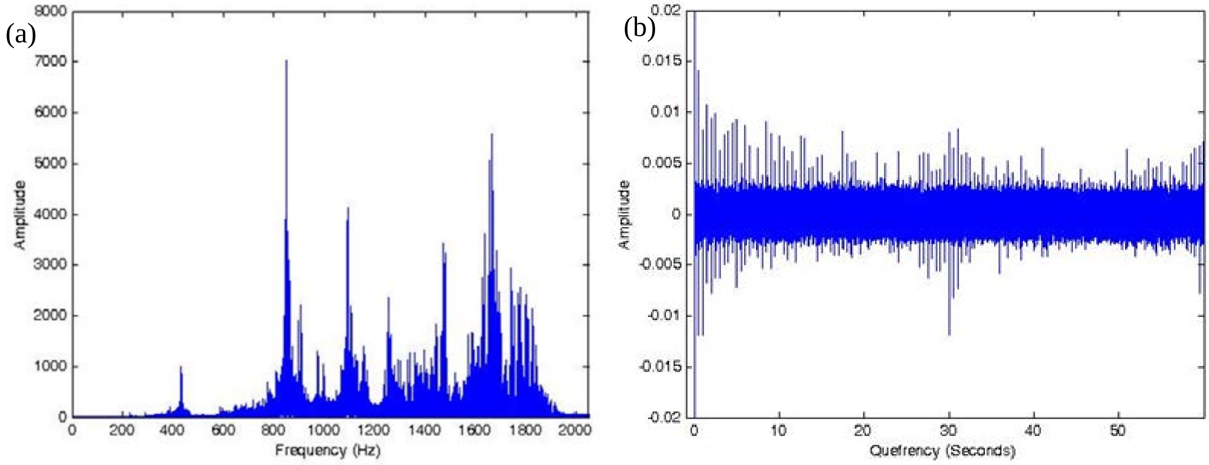

Figure 8 – Resampling to time domain (a) Spectrum (b) Corresponding cepstrum

Thus, as mentioned above, a further exponential lifter was applied to remove these disturbances and concentrate on the modal information at low quefrencies. The time constant used was 400 lines (half that in the rotation angle domain since the average sampling rate was about the same) so this would dominate in determining the final damping factor. In fact, the 400 samples correspond to $\tau = 16$ ms, so that the damping factor $\sigma = 1/\tau = 62.5$ rad/s or 10 Hz, meaning that the added damping adds 20 Hz to the 3 dB bandwidth of all modes (which can be compensated for after OMA has been carried out).

The final resulting spectrum is shown in Figure 9, on both linear and dB amplitude scales.

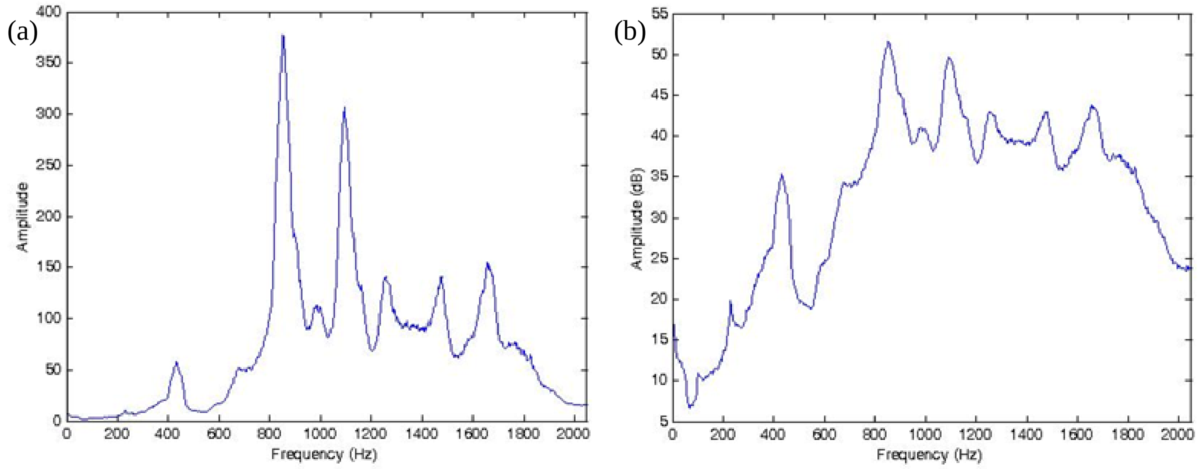

Figure 9 Final spectrum after order removal and added damping (a) Linear scale (b) dB scale

5. OPERATIONAL MODAL ANALYSIS (OMA)

Even though only the spectra are shown here, it should be kept in mind that corresponding time signals can be regenerated using the original phase. This is of course noisy, but as shown in (4) the OMA software is still able to extract the modal information because of the averaging inherent in the extraction of cross spectra as part of the OMA process.

Unfortunately, there was not time to carry out the OMA on this data, and since the force measurements made at the same time as the response measurements were faulty, there were no measurements of FRFs made at the same time with which to compare the results. However, some results of experimental modal analysis (EMA) on the same casing, using an impact hammer, were available, as reported in (2), and these should have similar natural frequencies, even if the mounting method was different. Figure 10 shows a typical FRF from that measurement series, on both linear and dB amplitude scales, where it is seen that many of the same, or similar, modal frequencies are present. As explained above, the damping of all modes is considerably higher, but this can in principle be compensated for. Note that the reference points for the OMA (shaker attachment point) and EMA (response accelerometer position) were not the same, so the measured FRF is not for the same

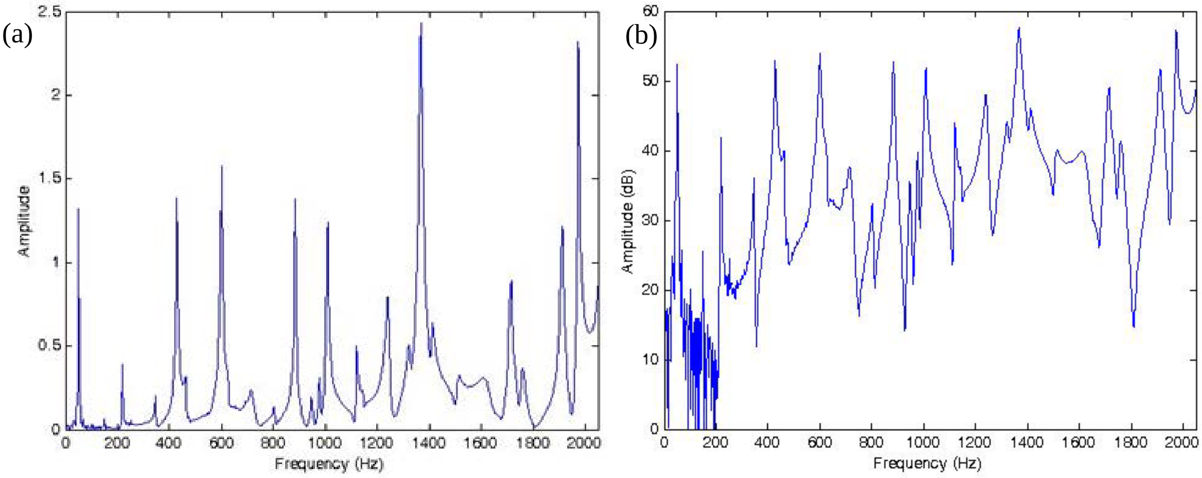

Figure 9 Similar FRF from EMA by impact testing (a) Linear scale (b) dB scale

input/output combination as the OMA response.

Thus, even though it is still to be demonstrated fully, it seems likely that the processing carried out here, to remove discrete orders in the angle domain, and then return to the time domain for OMA processing, should yield valid answers. The additional damping added by windowing the cepstrum can in principle be compensated for in the final results.

6. CONCLUSIONS

This paper describes a method whereby acceleration signals from machines with varying speed can be processed to remove the effects of discrete orders, which because of the speed variation are no longer periodic in the time domain, but are so in the rotation angle domain. Because of complications resulting from amplitude modulation, which is not removed by order tracking to the rotation angle domain, it was found convenient to remove the discrete orders using cepstral methods, which are less sensitive to this effect, and which at the same time concentrate the modal information at low quefrency at the expense of other disturbing influences. After removal of these deterministic components, it is possible to perform OMA on the residual signal, excited by broadband noise, but only after transformation back to the time domain.

At this stage the demonstration is only indicative, and it is hoped to fully validate it in future work.

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