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Repressing the effects of variable speed harmonic orders in operational modal analysis

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ABSTRACT

Discrete frequency components such as machine shaft orders can disrupt the operation of normal Operational Modal Analysis (OMA) algorithms. With constant speed machines, they have been removed using time synchronous averaging (TSA). This paper compares two approaches for varying speed machines. In one method, signals are transformed into the order domain, and after the removal of shaft speed related components by a cepstral notching method, are transformed back to the time domain to allow normal OMA. In the other simpler approach an exponential shortpass lifter is applied directly in the time domain cepstrum to enhance the modal information at the expense of other disturbances. For simulated gear signals with speed variations of both $\pm 5\%$ and $\pm 15\%$, the simpler approach was found to give better results The TSA method is shown not to work in either case. The paper compares the results with those obtained using a stationary random excitation.

1. Background

With a scaled modal model of a structure 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. Scaled modal models can be obtained using Experimental Modal Analysis (EMA). In principle, this requires the simultaneous measurement of both forces and responses, typically in the laboratory, but in that case 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. It is normally assumed 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 algorithms as modes with very low damping. Over the years techniques have therefore been developed to remove discrete frequency components before further processing. A number of these have used order tracking to convert from the time domain to the rotational angle domain (and thus the frequency domain to harmonic order domain). The earliest publications were four papers by Lembregts et al. in 1996, of which a typical one is Ref. [1]. Although it was implied that the order tracking could be reversed after harmonic order removal, so as to have modal information correctly

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represented in the normal frequency domain, no details were given. Later Groover et al. [2] presented the concept of using a reversible order-tracking approach as being novel, possibly being unaware of the earlier work by Lembregts et al. [1]. Even though Groover et al. describe the situation as being fairly general, the practical example given is for almost constant speed, and the order tracking used primarily to remove windowing effects and the repetitive errors from the zebra tape used for order tracking. In 2007 Peeters et al. [3] presented a method to use reversible order-tracking to remove order-based components from a varying speed response signal, in order to pre-filter the signal, before then using OMA. They referenced Lembregts et al. [1] as the origin of the procedure. While this is very similar to the work proposed by Groover et al. [2], it represents the first instance of reversible order-tracking being specifically and explicitly employed for the application of OMA. Thus, most previous practical applications were for relatively small speed fluctuations so that the difference between the order and frequency domains was primarily one of scaling, and they are treated in the following as nominally “constant speed”.

1.1. Harmonic removal at constant speed

The initial approach to harmonic removal in [1,3] was based on Time Synchronous Averaging (TSA), where the periodic components are found by averaging them synchronously with the repetition period. In [3] the implementation was slightly different in that the removal was done in the frequency (order) domain after order tracking had reduced harmonic orders to single lines.

In [3], the procedure was applied to the response signals of a helicopter in steady flight where the harmonics to be removed were those of the rotor speed. As mentioned above, even at constant speed, a necessary precursor to TSA is order tracking, also known as angular resampling, whereby signals are resampled at equal intervals of rotation angle rather than time, with an integer number of samples per revolution, and fixed starting phase, so that the averaging can be performed over exactly one cycle of the fundamental frequency. The TSA result for one period can then be repeated periodically and subtracted from the total record, to leave a residual signal without discrete frequency components at integer multiples of this fundamental frequency. This process has to be repeated (with separate resampling) for every different non-commensurate excitation frequency. For constant speed, the resulting “order spectrum” in terms of harmonic orders, will be a scaled version of the normal frequency axis, and as long as the speed variation is only a fraction of a percent, the modal information will not be significantly distorted.

In [4], an alternative cepstral approach was introduced, where the cepstrum was used on the same data in two ways: targeted removal of families of harmonics using a “notch lifter”, and using an exponential “short pass lifter” to enhance modal information at the expense of most other disturbances. For approximately constant speed, this does not require prior order tracking. As shown below, multiplication of the cepstrum, even of stationary signals, by an exponential window simply increases the damping (of each mode) by an amount corresponding to the window (as for exponential windows used on transient signals in impact testing) and this can be removed later. The results of this approach were found to be comparable with the TSA method, although the first harmonic was not completely removed and was still treated as a lightly damped mode. This could be seen to be data dependent, as the time constant of the exponential lifter was of the order of the fundamental periodicity and did not entirely exclude it.

1.2. Harmonic suppression at variable speed

If the speed varies somewhat, 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 use a different approach. In [5], and expanded on in [6], an approach was attempted where order tracking was first used to convert to the order domain, where the speed synchronous components could be removed. In [5,6] the two cepstral methods from [4] were applied in the order domain rather than using TSA, as explained below. However, the time constant of the exponential window applied in the order domain was smeared over the same range as the speed variation, and so a further exponential window was applied after transformation back to the time domain, but shorter by a factor of about 2, so that it would dominate in the final result. The order tracking operation was then reversed back to the time domain in order to carry out OMA on the signals with order related components removed.

It should be noted that in general (with varying speed) TSA cannot be used for the removal of order related components, as order tracking removes frequency modulation, but not amplitude variation with speed. The latter can be because of passage of certain orders, such as gearmesh frequencies, through resonances, or possibly because of accelerations and decelerations associated with the speed variations. The frequency of speed variation is not necessarily related to the harmonic series being removed. Because of amplitude variation along the record, the result of TSA will just give some “average” amplitude (and phase), and the result of subtracting it will still contain some part of the deterministic order related excitation.

The results in [5] appeared reasonable, but with broad resonance peaks because the required exponential time constant to smooth the response spectra was quite large. It was found that the original measurements suffered from a problem of discontinuities in the original excitation signals, and the current paper rectifies that problem as well as proposing a simpler approach which appears to perform well (or better) in most cases. The first application of this approach, presented in [7], used selected sections of the data from [5] avoiding the discontinuities.