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Implementation of low-kurtosis pseudo-random excitations to compensate for the effects of nonlinearity on damping estimation by the half-power method

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ABSTRACT

Pseudo-random excitation with low crest factor is less likely to force a structure under test into nonlinear behavior, which should be avoided, or at least minimized, in the practice of experimental modal analysis. However, simply cutting high peaks and removing them from the excitation time history is not an option because such clipping of the signal introduces frequency distortions of the amplitude spectrum. A better approach is to manipulate phases of the harmonics before generating the time history instead of clipping it afterwards. To do so a new parameter, kurtosis, is used in this paper to characterize the high peak behavior of pseudo-random excitations. An analytical solution is obtained for how the phases should be selected in order to reduce kurtosis and make modal testing excitations smoother with less extreme peaks. This solution was implemented for evaluation of the damping ratio of a SDOF system by the half-power method in the presence of an additional cubic term in the equation of motion. The system response obtained by numerical integration was treated as modal analysis data and the result is that the kurtosis-optimized excitation has compensated for the effect of nonlinearity and allowed to identify the damping ratio with good precision whereas an ordinary Gaussian excitation with randomized phases caused an error of 75 percent. Comparison with the numerical crest factor minimization by time-frequency-domain swapping has been made and experimental results from a modal testing rig with a realistic turbine blade are also presented in the paper.

1. Introduction

Although theoretical methods and computational tools are constantly progressing, there will always be a necessity to verify model parameters by experimental tests. The most effective way of doing so is to impose an excitation force by a shaker actuator and to measure the corresponding dynamic response of the object under test. In this case there is an opportunity for a test engineer to choose the most appropriate excitation and to have more accurate and easily available measurements in the laboratory rather than those from real service conditions.

Estimation of the system frequency response function (FRF) via modal testing [1,2] is currently a key technology in structural dynamics analysis and has become a must in the process of mechanical product design. Initially modal testing had been sinusoidal through the use of stepped-sine excitations. Then, due to the invention of the Fast Fourier Transform (FFT)

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and digital signal analysis, it became possible to take measurements in much less time by implementing broadband excitations with all frequencies of the required range generated simultaneously, not one by one as with the stepped-sine excitation.

A broadband pseudo-random excitation consisting of harmonic components at the frequencies $f_n = n\,\Delta f$ equal to integer multiples of the FFT frequency increment Δf can be generated to identify resonances and notches in the FRF of the dynamic system under consideration. Actual time histories to be sent to the shaker input are created from the required amplitude spectrum A_n by the Inverse Fast Fourier Transform (IFFT). It means that the shaker is driven by a multi-frequency signal

$$x(t) = \sum_{n=1}^{N} A_n \cos(2\pi n \Delta f t + \varphi_n) \tag{1}$$

where the phase angles φ_n are normally defined as random variables uniformly distributed in the range from $-\pi$ to π radians.

The excitation obtained in such a way is periodic with a period $T = 1/\Delta f$; however, when the number of frequency components N is large, the time history within the period appears to be quite chaotic. That is why, in modal analysis terminology, this excitation is called pseudo-random as a possible alternative to pure random excitations [1,3,4]. Signal periodicity in pseudo-random testing allows to avoid leakage error inherent in pure random testing.

While the amplitudes A_n are committed to prescribing the excitation power spectrum, much flexibility still remains in the choice of phases φ_n. If another set of random values is used with the same amplitudes A_n, a new signal obtained from Eq. (1) will have exactly the same amplitude spectrum despite of the fact that its time history is different from the first one. A number of such pseudo-random signals with a constant spectrum but varying random phases can be applied one by one as periodic random testing [1,4,5] with a subsequent averaging of the results of the repetitive FRF measurements to remove any possible noise and distortions.

The technique of periodic random testing combines the best features of pure random and pseudo-random excitations by providing better precision because of averaging, and also eliminating leakage problems [4]. Even more can be achieved if the phases are not only varied in periodic random testing but also selected each time in a special way. It is known [6] that the phase spectrum can be rearranged such that high peaks are not present in the excitation signal, thereby allowing a better signal-to-noise ratio.

Another advantage of a smooth excitation is that it is less likely to force the structure under test into nonlinear behavior, which should be avoided, or at least minimized, in the practice of experimental modal analysis. This is a focal point of the current paper and a new method of phase selection is suggested for generating pseudo-random excitation with high peaks removed from it. A numerical evaluation was also performed for analysing to what extent modal testing excitations of this kind can compensate for the influence of nonlinearity in the example of damping estimation by the half-power method.

2. Crest factor, clipping, and time-frequency-domain swapping

To characterize how distinctive high peaks are in the signal time history the crest factor (CF) parameter is normally used. It is a ratio between the absolute value of the largest time history point $|x(t)|_{\max}$ and the root-mean-square (RMS) value σ of the signal

$$CF = \frac{|x(t)|_{\max}}{\sigma} \tag{2}$$

If random phases φ_n are put into Eq. (1) when generating a pseudo-random excitation, the highest peak amplitude appears to be several times larger than the RMS value. For an 8192-point IFFT transform with amplitudes A_n of all harmonics in Eq. (1) equal, the crest factor between CF=4.5 and CF=5.0 can typically be observed for a time history consisting of 100 IFFT blocks (periods) of the generated pseudo-random signal.

It may look like there is an easy and straightforward way of reducing crest factor by simply clipping everything that is higher than the specified limit and removing it from the pseudo-random signal generated by the standard procedure with random phases φ_n in Eq. (1). However, if any alterations are made to the time history after it has been IFFT-generated, the signal power spectrum will no longer correspond to the target profile prescribed for IFFT generation.

The amplitudes A_n of the harmonic components will change since signal clipping produces frequency distortions that are another kind of energy leakage, now not because of the signal non-periodicity but because of the square-wave shape of the clipped peaks. Apart from these changes in the IFFT amplitude spectrum A_n, the sigma clipping procedure results in superfluous excitation components appearing outside of the prescribed bandwidth at the frequencies where the amplitudes of the harmonics were zero-valued initially. This may lead to unwanted vibration modes being excited.

Another issue with clipping is that, when a digital shaker controller is used in modal testing to make the excitation amplitude spectrum uniform, the controller's performance at the system resonances will be badly affected by frequency distortions resulting from clipping. If an excessive peak in the amplitude spectrum of the force transducer signal is detected then the closed-loop controller will need to decrease amplitudes A_n of the corresponding harmonics in the pseudo-random signal fed to the shaker amplifier input. Such a situation is depicted in Fig. 1 showing experimental results obtained on a turbine blade modal testing rig, which is described in more detail in Section 5.