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System identification of a linearized hysteretic system using covariance driven stochastic subspace identification

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A single mass Bouc-Wen oscillator with linear static restoring force contribution is approximated by an equivalent linear system. The aim of the linearized model is to emulate the correct force-displacement response of the Bouc-Wen model with characteristic hysteretic behaviour. The linearized model has been evaluated by the root-mean-square error between simulated response and the response history from two sets of experimental test data.

Hysteretic behaviour is encountered in engineering structures exposed to severe cyclic environmental loads, as well as in vibration mitigation systems such as magneto-rheological dampers. The mathematical representation of a hysteretic force can be obtained using the non-linear first-order differential equation

$$\dot{z}(y,\dot{y}) = \alpha\,\dot{y} - \beta\left(\gamma\,|\dot{y}|\,z\,|z|^{\nu-1} + \delta\,\dot{y}\,|z|^{\nu}\right) \tag{1}$$

known as the Bouc-Wen model [1, 2]. The shape and smoothness of the hysteresis loop is controlled by model parameters: α, β, γ, δ and ν.

The non-linear hysteretic force governed by the Bouc-Wen model in (1) is approximated by a linear model of the form

$$z(y,\dot{y}) = \lambda\,y(t) + \kappa\,\dot{y}(t) \tag{2}$$

The individual coefficients in (2) are determined by assuming sinusoidal motion constant over one period with amplitude A, applying harmonic averaging and integration over the full vibration period with angular frequency ω,

$$\lambda = \frac{9\,\pi^2\,\epsilon}{32\,A^2\,\mu + 9\,\pi^2} \quad , \quad \kappa = \frac{12\,A\,\mu\,\pi\epsilon}{\omega(32\,A^2\mu^2 + 9\,\pi^2)} \quad \textit{where} \quad \epsilon = \alpha - \beta\,\delta \quad , \quad \mu = \beta\,\gamma \tag{3}$$

These approximations are exact for vanishing non-linearity in z, associated with the power coefficient ν approaching unity.

The input-output test data has been provided in [3], wherein the individual data sets are described. The random phase multi-sine data set contains the steady-state response, while the sine-sweep data set is excited such that the response is not in steady state. The natural frequency and damping ratio of the test systems have been estimated from the displacement time history, using a covariance driven stochastic subspace identification algorithm (COV-SSI) [4], implemented in MATLAB. The number of block-rows in the Toeplitz matrix and the model order have been selected based on a minimization of the squared residual between the estimated natural frequency and damping ratio, and the corresponding equivalent parameters obtained from the decay of the unbiased covariance estimate.

The response has been simulated using a fixed time-step fourth-order Runge-Kutta time integration scheme, with the sample interval of 1/20 of the period and with zero initial conditions. The root-mean-square errors e_{rms}, relative to the model and the test output time series are $7.9 \cdot 10^{-5}$ m and $1.1 \cdot 10^{-4}$ m for the multi-sine and sweep-sine data sets, respectively. The error measure e_{rms} has been scaled by the number of points in the time series, in this case 8192 and 153000 for the multi- and sweep-sine data sets, respectively.

The present approach is suitable for simulations of steady state response of a single-degree-of-freedom system, where the main advantage lies in its simplicity. For simulations of unsteady response the assumption of sinusoidal motion is obviously violated. Furthermore, the assumptions of the estimated covariance function will also be violated and in particular the estimates of the damping ratio by the COV-SSI will be erroneous.

References

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