Modelling of nonlinear torsional flutter using Volterra models trained on experimental data

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SUMMARY:

This paper presents a two-stage wind tunnel test of a wedge-shaped section model of a bridge deck. First, the section model was suspended in a free vibration set-up, where it was observed a torsional flutter with limit cycle oscillations for several different wind speeds. Later, forced vibration tests were performed, where the section model motion was prescribed as the displacement history from the previously recorded limit cycle oscillations. Next, attention is given to a numerical non-linear Volterra model. Using the measured loads from the forced vibration tests as a ground truth, it is investigated if this numerical model can correctly reproduce the torsional force in the flutter conditions using displacements as model inputs.
The Volterra model is of the computationally effective Laguerrian type and has been trained using experimental data from a forced vibration experiment. The results show that the Volterra-models can predict the non-linear self-excited forces with good accuracy. Next step in the research is to use trained model to predict the nonlinear flutter motion gained in the free-vibration rig.

Keywords: Nonlinear aerodynamics, Volterra models, bridge aerodynamics

1. INTRODUCTION

In traditional bridge engineering design, the critical wind speed limit of flutter is an absolute demand that the design needs to adhere to. In the linear domain, flutter is an instability where the response diverges since the damping is negative. However, if one considers nonlinearities, this singularity is necessarily not true, and multiple researchers has pointed out that the nonlinear contribution of the aerodynamics can limit the amplitude growth of the flutter motion, avoiding divergence. The phenomena have been called soft-flutter or nonlinear flutter with limit cycle oscillations (LCO). It is believed that the nonlinear component of the aerodynamical forces grow faster for increasing motion amplitudes than the linear parts, so that the system is self-stabilizing even for increasing amplitudes.

Building longer, more economically and environmentally friendly bridges is of key importance for the future of infrastructure. A nonlinear flutter criteria in design could help designers push the limits for long span bridges even further by utilizing the additional margins provided by nonlinear flutter.

An experimental campaign of testing a single deck cross-section in the free-vibration rig at Norwegian

University of Science and Technology (NTNU)performed. The tests found several LCO flutter events at different wind speeds. The tests were repeated several times to check the consistency of the limit behaviour, and a good repeatability was observed. To be able to understand the LCO phenomena better, the section model was later tested using a forced vibration rig (Siedziako et al., 2017) in the same wind tunnel. The prescribed motion of the bridge deck was similar to the displacement time histories in the free-vibration LCO. However, small test variations were also conducted, using for instance a slightly different amplitude or slightly different frequencies.

The data was used as a basis for comparing the behaviour in both free and forced motion and represented a significant amount of training data for model prediction. Therefore, a Laguerrian type Volterra-model, that is known to be able to model multiple types of nonlinearities (Skyvulstad et al., 2021), has been introduced for predictions. Multiple comparisons have been made:

I) Comparing forces in the free and forced vibration tests data for LCO types of motion
II) Investigating the Laguerrian models applicability to predict force data from LCO motions in forced vibration
III) Investigating the use of the Laguerrian models applicability for force estimation in a simple two-degree-of freedom model to predict the responses gained from the free-vibration rig

2. EXPERIMENTAL SETUP

The section model shown in Figure 1 was tested in the free and the forced vibration rigs at NTNU. In the free vibration rig, gradually increasing smooth wind slowly towards the onset point where an increase in amplitude of the flutter motions takes place. A time-series of the torsional rotation in a typical LCO development is shown in Figure 3.In Figure 2 the increase of the mean peaks of the LCO is shown for increasing wind speed.

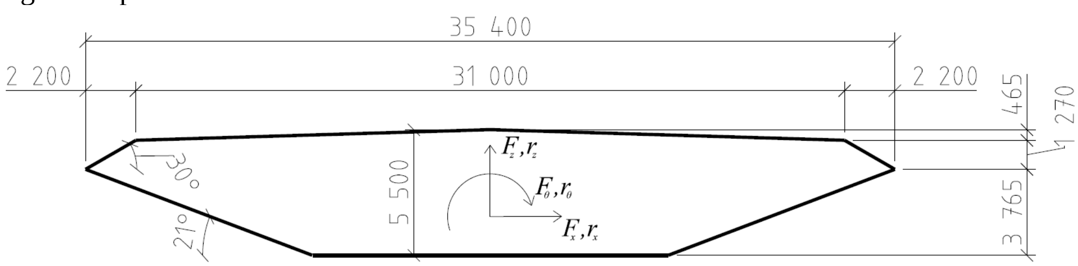

Figure 1. Cross-section tested in the wind tunnel

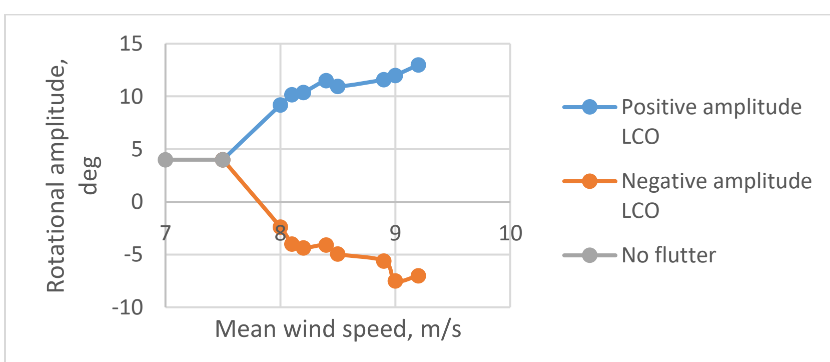

Figure 2. Mean peak value of limit cycle oscillations, torsional motion for different wind speeds

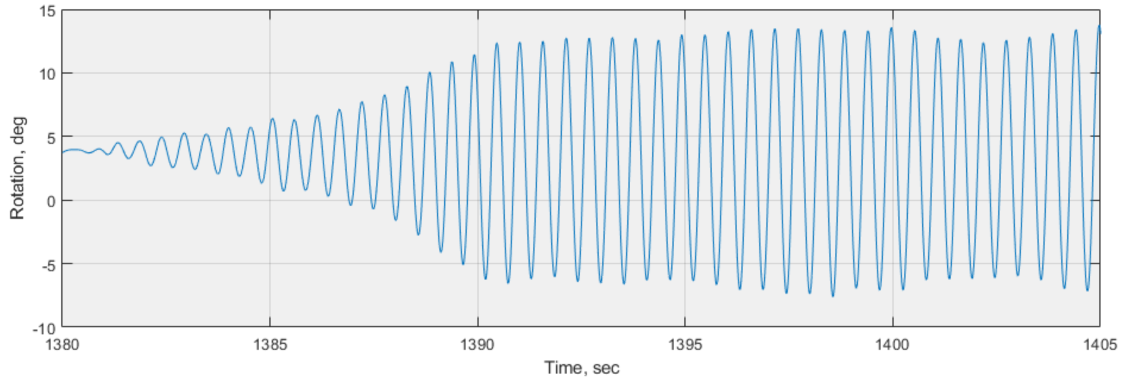

Figure 3. Time series of the limit cycle oscillation in torsion. 9 m/s smooth flow.

3. MODEL PREDICTION

The Laguerrian Volterra model (Skyvulstad et al., 2021) is introduced for model prediction. The Laguerrian Volterra model is a parameterization of the classical Volterra-model into a function basis of Laguerrian filters. The filters are mutually orthonormal onto each other, and the filters are completely determined by a decay factor and the filter order. A single-input-single-output p^{th}-order Volterra model with memory M can be given as follows (Westwick, Kearney, 2003):

$$F[n] = h_0 + \sum_{k=0}^{M} h_1[k] r[n-k] + \sum_{k_1}^{M} \dots \sum_{k_p}^{M} h_p[k_1, \dots, k_p] r[n-k_1] \dots r[n-k_p] \quad (1)$$

Where, F, denotes the self-excited forces, r, denotes the motions and h_p represents the p^{th}-order unknown Volterra kernels to be determined. The kernels are further parameterised using a superposition of Laguerrian filters as follows:

$$h_1[k] = \sum_{l=0}^{J} c_l g_l[k] \quad (2)$$

$$h_P[k_1, \dots, k_p] = \sum_{l_1=0}^{J} \dots \sum_{l_p=0}^{J} c_{l_1 \dots l_p} (g_{l_1}[k_1] \dots g_{l_p}[k_p]), \quad p > 1 \quad (3)$$

$$g_l[k] = \alpha^{(k-l)/2} (1-\alpha)^{(1/2)} \sum_{i=0}^{l} (-1)^i \binom{k}{i} \binom{l}{i} \alpha^{l-i} (1-\alpha)^i, \quad k \geq 0 \quad (4)$$

Where c denotes the unknown filter coefficients, l denotes the filter number and $0<\alpha<1$ denotes the decay factor, also to de determined. Now, the problem is parameterized, but the problem of identification is increased by one order, namely the unknown filter coefficients c, and the decay factor α. The large benefit of using this, is that the number of unknowns c is significantly less than the unknowns in the Volterra-kernels, and the model is also quite robust in the choice of the decay factor meaning that a trial-and-error approach of finding a suitable decay factor is reasonable. Setting the decay factor constant, reduces the identification to a linear least squares identification:

$$\arg\min_\theta (\|F - \boldsymbol{X}\theta\|_2^2) \quad (5)$$

Where $\boldsymbol{X}$ denotes a stacked regression matrix of the filters on the inputs r, θ denotes a parameter vector containing the filter unknown filter parameters c.

4. PREDICTION RESULTS

Figure 4 shows the forces from a forced vibration experiment with a limit cycle oscillation similar to the one seen in free vibration. The figure also shows a Volterra series prediction of the forces on the same motion series. Here, one can see that the forces are predicted with reasonable accuracy.

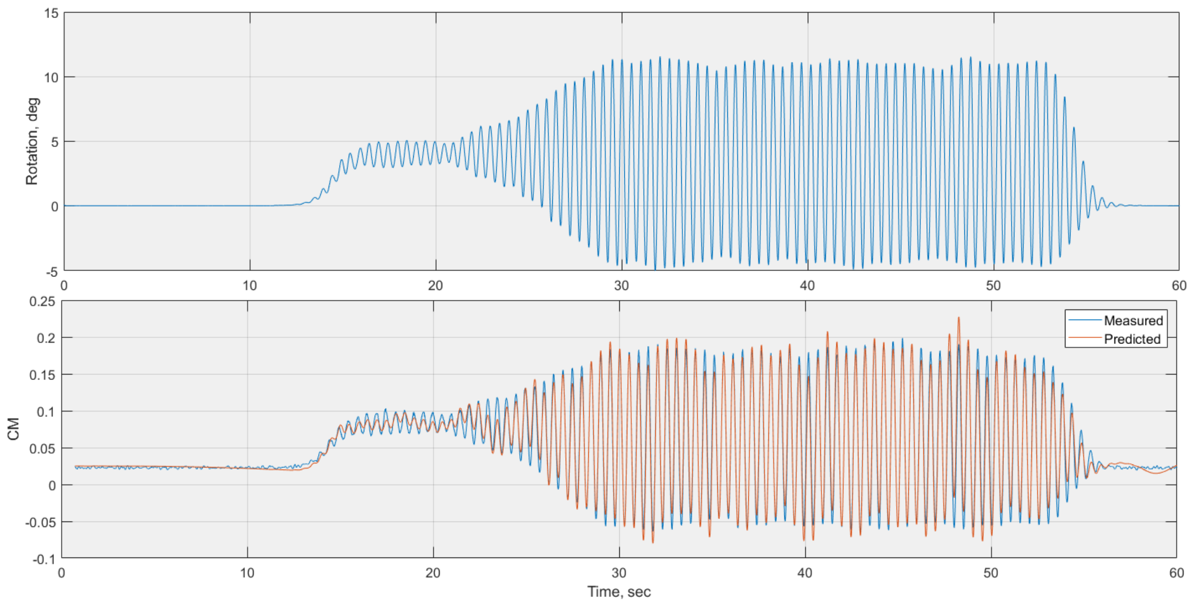

Figure 4. Top: Motion in the wind tunnel, Bottom: Pitching moment, measured and predicted

7. CONCLUSIONS AND FURTHER WORK

A section model has been tested in the forced and free vibration rig at NTNU. Torsional flutter LCO's where observed for multiple wind speeds in the free vibration rig, and the similar motions where forced in the forced vibration rig. A Laguerrian type of motion was able to predict forces relatively well from the motions in the forced vibration rig. Further, the load models is going to be used to predict the responses in the free-vibration rig using the Laguerrian load model trained on data from the forced vibration rig.

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