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Integrated aerodynamic and structural optimization of a suspension bridge with an aluminum girder using surrogate models

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SUMMARY:
Several suspension bridges are currently under planning in Norway. There is an industrial and societal interest in designing some of these with a girder made from recycled aluminum since a lighter bridge deck will reduce costs for cables and towers, and since aluminum is easier to maintain than steel. However, a more lightweight bridge will increase the susceptibility of vortex-induced vibrations, buffeting response, and reduce the flutter stability limit. This paper presents a framework for combined aerodynamic and structural optimization of a suspension bridge to ensure that the alternative with a lighter girder fulfills all requirements set by the authorities. The methodology is based on: *i)* aerodynamic data from wind tunnel tests of 11 different section models; and *ii)* a fully parametric suspension bridge finite element model providing the vibration modes for a given bridge structural design. Results show that a bridge design with a flutter stability limit of 84 m/s is obtained.

Keywords: Wind tunnel, flutter stability, aluminum bridge, suspension bridge

1. INTRODUCTION

Major investments will be made to upgrade road infrastructure in Norway in the coming years. At the same time, it is desired to minimize the carbon footprint. Using recycled aluminum is an attractive way of reducing emissions, but there is currently not much experience in using this material in large bridges.

Using an aluminum bridge deck leads to considerable weight reductions, which will reduce costs for the cables and the two towers. It is however well known that reducing the mass will make the bridge more prone to vortex induced vibrations, buffeting response, and reduce the flutter stability limit. The design challenge calls for integrated aerodynamic and structural optimization to make a cost-effective and safe bridge design.

This contribution considers the proposed Langenuen suspension bridge, a single-span suspension bridge with a main span of 1235 meters, where we present a framework for integrated aerodynamic and structural optimization. Surrogate models based on Gaussian process regression are adopted for the aerodynamic properties of the bridge cross-section. In addition, the vibration modes are obtained from a finite element model that is automatically generated from a list containing structural and geometrical parameters. Wind tunnel tests of eleven different sections, with and without guide vanes, are used as the basis for the aerodynamic surrogate models used in the response and flutter assessment. The results show that the optimization based on surrogate models is a promising tool in designing new bridges and that wind tunnel testing results can be utilized in a more efficient manner for future bridge design. Limitations of the proposed methodology are also discussed.

2. SURROGATE MODELS BASED ON GAUSSIAN PROCESS REGRESSION

In practical applications of machine learning, Gaussian process regression has become a popular tool for surrogate modeling due to its simplicity, flexibility, and probabilistic nature. The technique is based on assuming prior multivariate Gaussian distribution that is defined by a mean function *m* and a covariance function *k*:

$$m(\mathbf{x}) = \mathrm{E}[f(\mathbf{x})], \quad k(\mathbf{x}_i, \mathbf{x}_j) = \mathrm{E}[\left(f(\mathbf{x}_i) - m(\mathbf{x}_i)\right)\left(f(\mathbf{x}_j) - m(\mathbf{x}_j)\right)^{\mathrm{T}}] \tag{1.1}$$

The prior Gaussian distribution of $f(\mathbf{x})$ is thus given by

$$f(\mathbf{x}) = GP\left(m(\mathbf{x}), k(\mathbf{x}_i, \mathbf{x}_j)\right) \tag{1.2}$$

Provided that a limited number of noisy observations $\mathbf{y} = f(\mathbf{x}_o) + \boldsymbol{\eta}$ are available, predictions at unobserved locations $\mathbf{x}_*$ are given by the posterior distribution (Rassmussen and Williams, 2006):

$$\hat{f}(\mathbf{x}_*) = GP\begin{pmatrix} k(\mathbf{x}_*, \mathbf{x}_o)[k(\mathbf{x}_o, \mathbf{x}_o) + \sigma_n{}^2\mathbf{I}]^{-1}\mathbf{y} + m(\mathbf{x}_*), \ \ldots \\ k(\mathbf{x}_*, \mathbf{x}_*) - k(\mathbf{x}_*, \mathbf{x}_o)[k(\mathbf{x}_o, \mathbf{x}_o) + \sigma_n{}^2\mathbf{I}]^{-1}k(\mathbf{x}_o, \mathbf{x}_*) \end{pmatrix} \tag{1.3}$$

The covariance of the noise is $\mathrm{E}[\boldsymbol{\eta}\boldsymbol{\eta}^{\mathrm{T}}] = \sigma_n{}^2\mathbf{I}$. Eq. (1.3) provides the closed-form expression for surrogate predictions and their uncertainties expressed as a multivariate normal distribution.

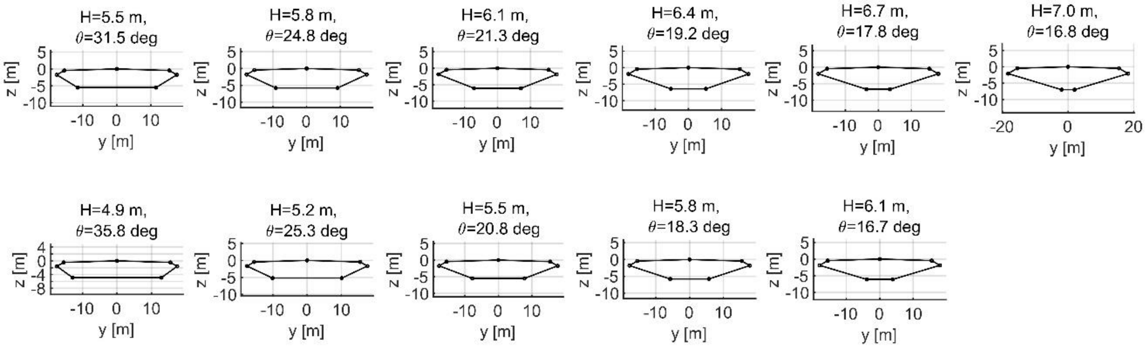

Figure 1: Cross-section geometries used to obtain the surrogate models. The six top sections have area 2.52 m^2 and torsional constant 29.1 m^4; the five bottom sections have area 2.55 m^2 and torsional constant 24.2 m^4.

2. WIND TUNNEL TESTS

Making a general surrogate model capable of modeling the aerodynamic properties of a bridge deck is a very challenging task. One of the major challenges is that many geometrical parameters define the shape of the section; therefore, some constraints are introduced in this work. Firstly, the geometry of the road surface is defined by following the regulations given by the road authorities. Secondly, we used the girder height (H) and the inclination angles of the lower part (θ) as parameters in the optimization. To further reduce the number of wind tunnel tests to a realistic number, it was decided to introduce a relation between H and θ; this constrains the cross-sectional area to a given number. The consequence is that the torsional stiffness of the girder, a very important parameter for the flutter stability limit, remains the same in the optimization.

Figure 1 shows the eleven sections used to obtain the surrogate models for the aerodynamic properties. One surrogate model is obtained for the six sections at the top of Figure 1, and another for the bottom five sections since these have different torsional stiffness. Figure 2 (middle, right) shows one of the sections during wind tunnel testing.

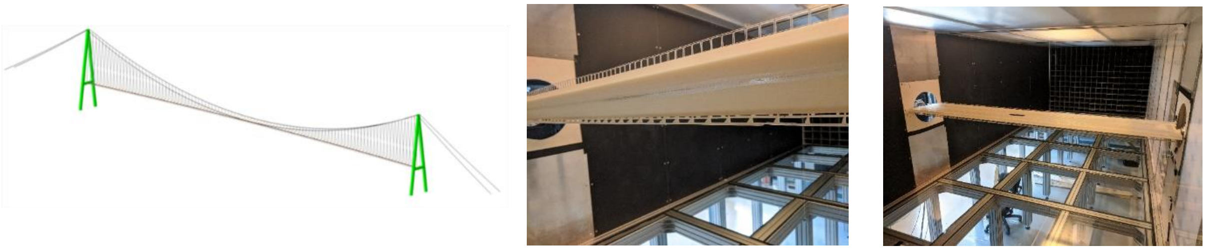

Figure 2: Left: finite element model; middle: close-up photo of a section model with barriers and guide vanes; right: entire section model in the wind tunnel.

3. THE PARAMETRIC FINITE ELEMENT MODEL OF THE BRIDGE

A parametric finite element model of the suspension bridge is made in the software ABAQUS. Figure 2 (left) shows a picture of the finite element model in one particular configuration. The parametrized model tool is openly available, see (Petersen, 2023), and can generate models from a list containing structural and geometrical parameters. The tower height, the distance between the main cables at the top of the tower, and the cross-sectional properties of the girder are chosen as parameters in the optimization.

4. SURROGATE MODEL OF AERODYNAMIC PROPERTIES AND OPTIMIZATION

By using the Gaussian process regression described in Section 2, the surrogate models for the aerodynamic properties are generated. One instance is shown in Figure 4, where aerodynamic derivatives for damping are shown as a prediction based on the girder height (H) and reduced frequencies (K). The popular squared exponential covariance function has been used as the kernel. Similar models are obtained for aerodynamic stiffness, and static load coefficients, but are not shown here for brevity.

Preliminary results for the flutter stability limit are shown in Figure 5. Flutter stability limits vary between 65 and 84 m/s for the tested sections, where the girders with heights in the range 5.5 -

6.1 m have the best stability performance. This research will further make use of the surrogate models to optimize the design of the bridge; material and cost savings compared to a steel bridge alternative will be critically examined.

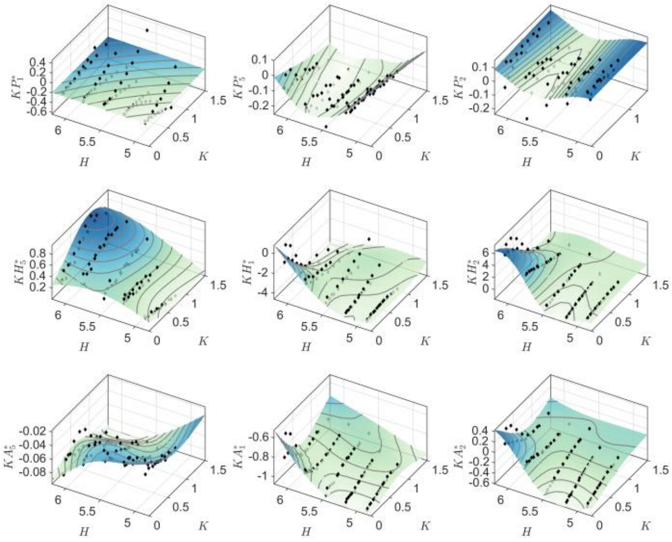

Figure 4: Surrogate models for the damping aerodynamic derivatives related to damping. The black dots represent the observed data, and the surfaces are generated by the predictions of the surrogate model.

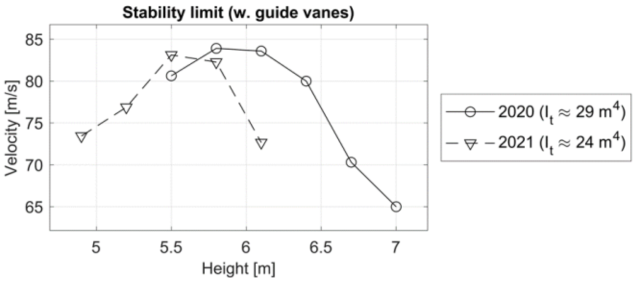

Figure 5: Flutter stability limit for the eleven sections shown in Figure 1.

6. CONCLUDING REMARKS

This work has presented a case study of aerodynamic and structural design optimization of a suspension bridge with an aluminum girder, a non-conventional material in the context of long-span bridges. The results show that a design having a flutter stability limit of approximately 84 m/s wind speed is possible. This research will further answer the question of material cost savings compared to a steel bridge girder alternative.

REFERENCES

Rasmussen, C., and Williams, K.I., 2006. Gaussian processes for machine learning. Cambridge, MA: MIT press
Petersen, Ø.W., 2023. Github code repository. https://github.com/Oyvindwpetersen/abaqustools