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A study of bridge deck aerodynamics through full-scale surface pressure measurements

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Abstract

The paper investigates the transformation of the incident natural wind into fluctuating surface pressures around a bridge deck by the mean of surface pressure measurements. The field measurements are performed in the framework of the Lysefjord Bridge wind and vibrations laboratory. A bespoke pressure measuring system was deployed to monitor fluctuating wind-induced surface pressures around three chords of the bridge and complemented by sonic anemometer records. Furthermore, the analysis of the measurements is supported by wind tunnel studies focusing on the gust loading of a motionless section model of closed-box girder bridge decks. Topics of interest are the spanwise coherence of wind-induced forces, the potential limits of the strip assumption and the vortex shedding process.

1 Introduction

Joint measurements of turbulent wind velocity and pressure around the girder of a full-scale bridge offer a unique opportunity to study bridge aerodynamics. However, such measurements are rarely seen in wind engineering, partly due to numerous technical challenges (Isaksen, 2008; Styrk Andersen et al., 2022). The paper describes a custom-made pressure measurement system developed at the University of Stavanger (Norway) between 2019 and 2022 that has been deployed on the Lysefjord Bridge since 2021. The paper presents some promising preliminary results from the pressure measurement set-up, which is complemented by a dense array of research-grade 3D sonic anemometers deployed around the deck. The experimental setup aims to study the span-wise coherence of pressure fluctuations, the applicability of the strip assumption (Davenport, 1962; Larose, 1997) and the vortex shedding process.

2 Instrumentation and method

This Lysefjord Bridge crosses the inlet of a narrow fjord in southwestern Norway (58.9237°N 6.0985°E). The bridge has a main span of $446\,\mathrm{m}$, with its midspan located $55\,\mathrm{m}$ above the mean sea level. The complex topography around the bridge governs the prevailing wind direction and the local turbulence characteristics. Flows from north-northeast (from the inside of the fjord) or south-southwest (from the inlet of the fjord) are predominantly observed at the site (Cheynet et al., 2019), generally passing the bridge at skewed angles.

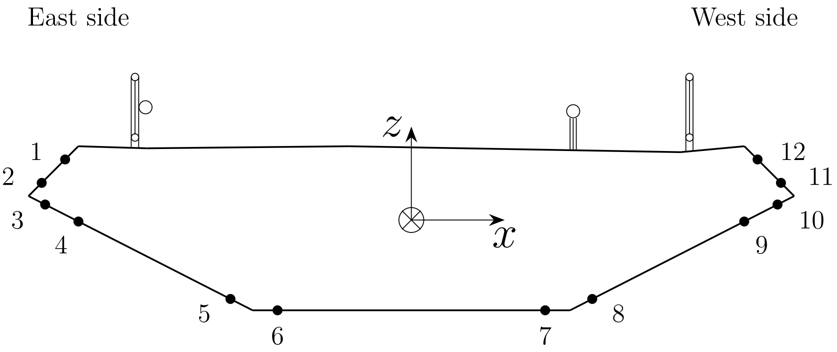

Figure 1. Pressure taps distribution for pressure strips A, B and C.

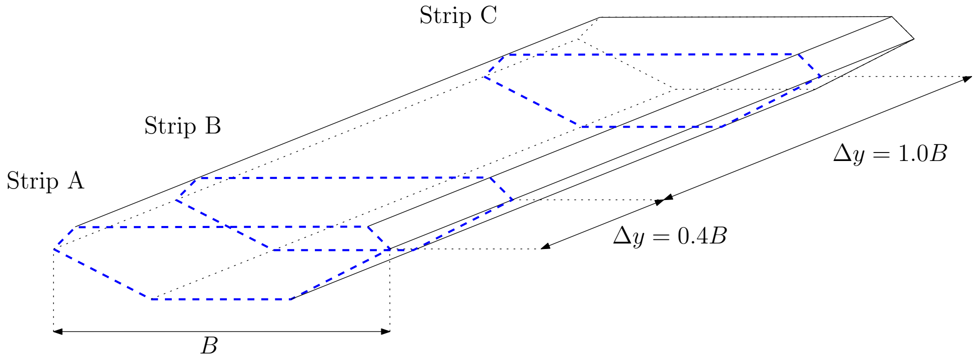

Figure 2. Span-wise separation of the pressure strips. Pressure strip A is located $5.8\,\mathrm{m}$ from the hanger H-08 cross-section, towards the mid-span.

The bridge deck cross-section is a hexagonal closed-box steel girder (see Figure 1) with a width-to-depth ratio of $B/D = 4.6$, where B = $12.3\,\mathrm{m}$ and D = $2.7\,\mathrm{m}$. The angle between the bottom plate and the lower side panel of the bridge deck is 27°. Whereas, the top inclined panels have an inclination of 45°. The bridge has a two-lane road with a cycle/pedestrian lane on the west side of the deck.

Since November 2013, the Lysefjord Bridge has been equipped with a Wind and Structural Health Monitoring system comprised of 3D sonic anemometers, and tri-axial accelerometers among others (Snæbjörnsson et al., 2017). In June 2021, a tailor-made pressure measurement system was installed on the bridge (Daniotti, 2022). Wind-induced surface pressures are measured along three cross-sectional strips along the main span of the bridge, between hangers H-08 and H-10. This part of the bridge is also densely instrumented with sonic anemometers.

The pressure measuring system comprises 36 pressure taps, distributed along three pressure strips, that are stretched around the bridge girder. Figure 1 sketches the layout of the pressure taps per strip. Locations where large variance of surface pressure is expected to occur for a typical closed-box girder bridge deck of a similar width-to-depth ratio are prioritized (Larose, 1997).

The pressure strips are referred to as Strip A, Strip B and Strip C. Strip A is positioned $5.8\,\mathrm{m}$ from hanger H-08, towards the middle of the main span. The normalized span-wise separations between the strips are $\Delta y/B = 0.41$, $\Delta y/B = 0.98$ and $\Delta y/B = 1.38$ (fig. 2). These distances were chosen mainly based on wind tunnel studies that investigated the span-wise correlation of fluctuating lift and overturning moment due to the buffeting wind action, in a simulated atmospheric boundary layer flow (Larose et al., 1998; Larose & Mann, 1998), based on spire-generated turbulence.

The pressure taps are identified using the character string XY, where $X = \{A, B, C\}$ traces the chord-wise pressure strip; $Y = \{1, 2, ..., 12\}$ denotes the location of the tapping point within a given chord-wise strip (see Figure 1 and Figure 2).

Each pressure tap is monitored using an analogue differential pressure transducer (ePressure V2.0 sensor from SVMtec GmbH). The reference static pressure is obtained from a controlled air volume located inside the girder. Atmospheric static pressure fluctuations are monitored using two omnidirectional static pressure probes (Moran & Hoxey, 1979) installed $4\,\mathrm{m}$ above the deck at hanger H-08.

3 Results

3.1 Vortex shedding process

Figure 3 shows the normalized spectra of surface pressures at the trailing edge for two different wind events, as a function of the reduced frequency $fD/\bar{u}$. The vertical turbulence intensity I_w is seen to dramatically change the power spectral density in the trailing edge surface pressure.

At low reduced frequencies ($fD/\bar{u} < 0.01$), the background turbulence is not significantly affected by the I_w. However, at higher frequencies, the vortex shedding frequency is clearly visible when $I_w = 0.07$ in terms of a spectral peak located at $fD/\bar{u} = 0.21$ on tap A09 (below the deck nose) and at $fD/\bar{u} = 0.15$ on tap A12 (above the deck nose). Interestingly, the spectral peaks appear detuned. Given the asymmetry in the cross-section, it is likely that the free shear layer above the deck nose has different characteristics than the one forming downstream of the bottom knuckle lines. Thus, owing to this asymmetry, vortices can be expected to shed with a slightly different frequency. The railings, including their partial blocking effects, may also contribute here to a certain extent.

Conversely, a high turbulence intensity ($I_w = 0.20$) tends to limit the formation of coherent vortex structures, partly because turbulence can increase the mixing and entrainment of the shear layers (Laneville et al., 1975). This effect is clearer above the deck nose for the case at hand, where no increase in the spectral level around the Strouhal number can be observed at pressure tap A12 .

3.2 Span-wise coherence of pressure fluctuations

For another wind event from South-west, with a mean wind velocity of 8.2 m s^{-1} and $I_w = 0.07$, the co-coherence γ_{pp} and quad-coherence ρ_{pp} between the two pressure signals at tap A01 and A04, are shown in Figure 4. The co-coherence peaks at around a reduced frequency $f_p = 0.18$ with $\gamma_{pp}(f_p) = -0.4$. Such a reduced frequency defines the St number for the case at hand. The negative peak value reflect the alternating shedding of vortices having opposite signs of vorticity and different phases, as shown by the non-zero quad coherence values around f_p. A noteworthy observation is, that the magnitude of the co-coherence at the shedding frequency is not negligible due to the favourable flow conditions, i.e. low TI and flow normal to the deck axis.

The co-coherence (see Figure 4), is characterised by a fairly broad-banded peak between $fD/\bar{u} = 0.15$ and $fD/\bar{u} = 0.23$. The lack of a significant narrow-banded correlation between the trailing edge surface

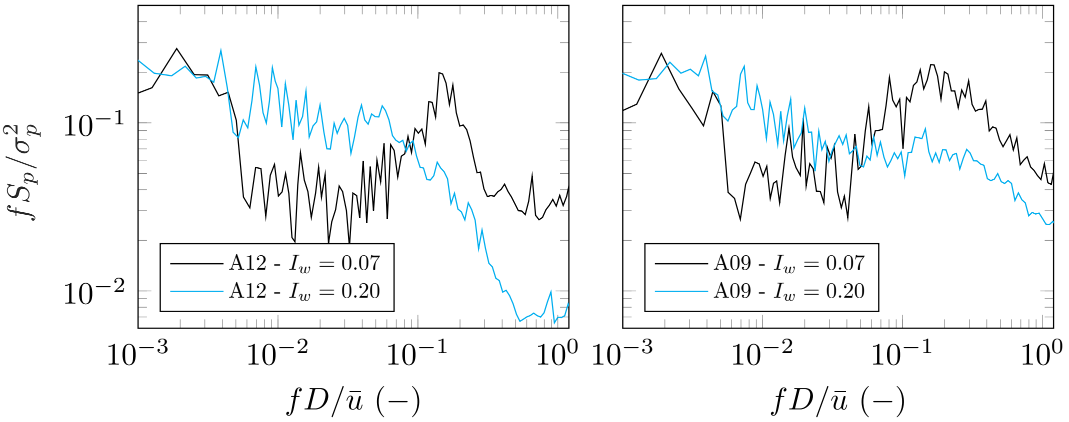

Figure 3. The influence of turbulence intensity on the normalized spectrum of the trailing edge surface pressures (A12, left panel and A09, right panel); dataset from 06/08/2021 and 27/08/2021.

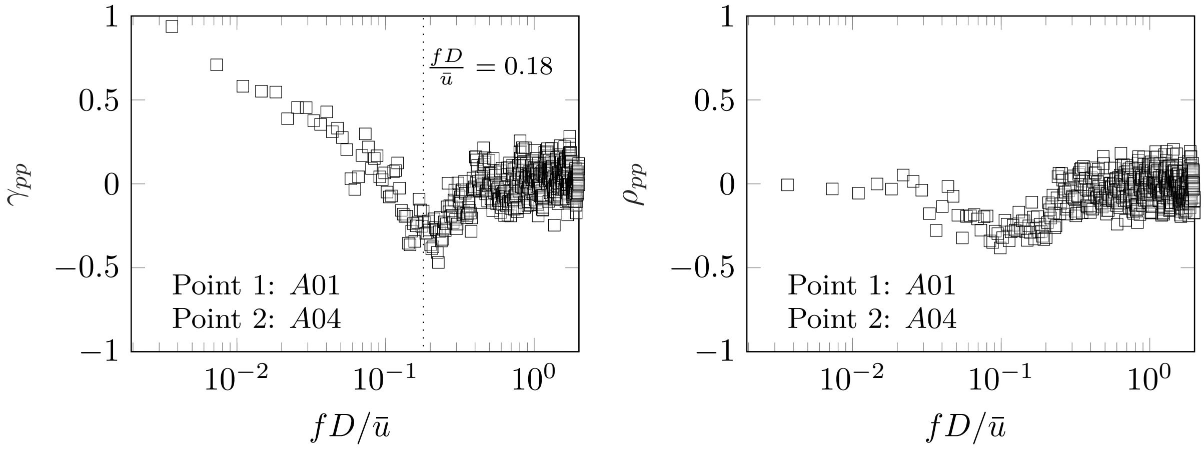

Figure 4. Co- (left panel) and quad-(right panel) coherence between surface pressures acquired on the trailing edge, i.e. tapping points A01 and A04; dataset from 14/06/2021, from 08:30 to 09:30 UTC.

pressures, both span-wise and at the same chord, may partly explain why the vortex-induced contribution to the (modal) lift is generally limited and, consequently, vortex-induced vibrations do not build up.

4 Conclusions

The paper describes specific aspects of the wind buffeting load generation in full-scale using surface pressures data and sonic anemometer records collected on the Lysefjord Bridge (Norway). The paper focuses on the gust loading and the vortex shedding process.

The bespoke pressure measuring solution installed on three strips around the deck allows for flexible measurements at multiple span-wise distances between the monitored deck cross-sections. Also, the pressure system can be expanded with additional tapping points. The measurement layout can be adapted for use on other bridges, without the need for drilling holes through the deck. We believe that the system developed, represents a valuable contribution that could inaugurate a breakthrough in pressure measurement techniques around closed bridge decks.

Records associated a relatively low turbulence intensity ($I_w \approx 0.07$) were exploited to explore the vortex shedding process. Owing to the asymmetry of the bridge deck, the non-dimensional vortex shedding frequencies associated with trailing edge surface pressured above ($St = 0.15$) and below ($St = 0.21$) the bridge deck nose are different. This may explain the lack of a narrow-banded (partial) lift force generated by the monitored trailing edge pressures.

The span-wise coherence of the surface pressure at the vortex shedding frequency is larger on the upper inclined surfaces of the girder. Increasing the ambient turbulence weakens significantly the formation of coherent vortex structures, both at the cross-sectional level and in terms of span-wise correlation.

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