

REFINEMENT OF THE CORRELATION LENGTH METHOD FOR PREDICTING VORTEX-INDUCED VIBRATIONS IN SLENDER STRUCTURES

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Abstract. *The effective correlation-length method, adopted in Eurocode 1 for predicting vortex-induced vibrations (VIV) of slender structures, has not been comprehensively validated across the full parameter space relevant to modern lightweight structures. This study presents new experimental results obtained in the boundary-layer wind tunnel of RWTH Aachen University. Using the forced-oscillation method, the influence of oscillation amplitude, wind-speed ratio, and boundary-layer turbulence on the correlation length was quantified for a circular-cylinder model with aspect ratio $\lambda = H/D = 25$ under smooth and turbulent flow conditions. To complement and validate these measurements, additional aeroelastic tests were conducted using a lightweight carbon-fibre tube model capable of reproducing self-excited vibration behaviour under resonance. The combined results confirm the consistency of both testing approaches within the lock-in range. Measured correlation lengths generally exceed current standard values across the entire amplitude range, a discrepancy attributable partly to the high aspect ratio of the test model. The aeroelastic tests further reveal a pronounced dependence of the lock-in range width on boundary-layer conditions, with direct implications for fatigue assessment. The findings support the need for a refined formulation of the correlation-length model.*

1 INTRODUCTION

Vortex-induced vibrations (VIV) play a major role in the design of slender structures such as chimneys and wind-turbine towers. The *effective correlation-length approach* (ECLA) models VIV through harmonic forces acting synchronously over a finite span—the correlation length. Its current form was presented by Ruscheweyh, who developed it using full-scale observations and wind-tunnel data [1]. Although the ECLA has proved effective over several decades, its calibration was based on a limited data set, and it does not allow explicit consideration of parameters such as aspect ratio, boundary-layer shear, and flow turbulence. Previous experimental studies by Toebe [2] and Novak and Tanaka [3] determined the correlation length only for small amplitudes ($Y/D \leq 0.1$), at sub-critical Reynolds numbers, using cross-section models without tip or shear effects, and covering at most two relevant parameters simultaneously.

As a result, an extensive wind-tunnel campaign was carried out to study the dependence of the correlation length on oscillation amplitude, wind-speed ratio, and boundary-layer turbulence. The measurements were performed using the forced oscillations method and aeroelastic free-vibrations. The forced oscillation tests enabled control of relative amplitudes and critical velocities, allowing for a broad investigation matrix, while the free-vibration tests were used to validate the forced oscillation results. An extract of both sets of results are compared with each other and with values from standards and literature.

2 WIND TUNNEL MEASUREMENTS

2.1 General set-up

All measurements were performed in the boundary-layer wind tunnel (BLWT) of the Center for Wind and Earthquake Engineering (CWE) of the RWTH Aachen University. The wind tunnel features a fully time-synchronized pressure measurement system. At the center of the turntable, a connector plate allows tower models to be mounted onto a massive foundation block, enabling the facility to induce pivoting base rotations for forced-oscillations test. For aeroelastic tests, the base was fixed in a rigid configuration. Figure 1 (a) shows the general setup and geometric definitions of the investigated tower structures.

Three boundary-layer simulations (BLS) were used in the measurements. The first one, BLS1, consists of a smooth flow BLS, where no roughness elements were located in the wind tunnel. The other two were obtained by placing different combinations of Counihan Roughness elements [4], so that terrain categories equivalent to TCI/TCII (BLS2, roughly $z_0 = 0.01 - 0.05$) and TCIII/TCIV (BLS3, roughly $z_0 = 0.3 - 1.05$) in the German national annex [5] were achieved. By considering the form and turbulence length scale of the simulated boundary layer profiles, a geometric scaling factor $\lambda_g = 1 : 90$ was chosen, so that the used models roughly represent stacks with height $H \approx 100m$.

2.2 Forced-oscillation measurements

The forced-oscillation model consisted of an aluminium tube with height $H = 1250$ mm and $D = 50$ mm (aspect ratio $\lambda = 25$), equipped with 21 pressure taps along a vertical axis at 120° towards the stagnation point, with identical pressure tube lengths to ensure phase synchronicity. The forced-oscillations test bench enabled parametric variation of oscillation frequency and amplitude. The parametric study covered relative oscillation amplitudes $Y/D = 0.00-0.71$ at sub-critical Reynolds numbers $Re = [0.4-1.9] \cdot 10^4$. The reference wind speed was measured at tower top.

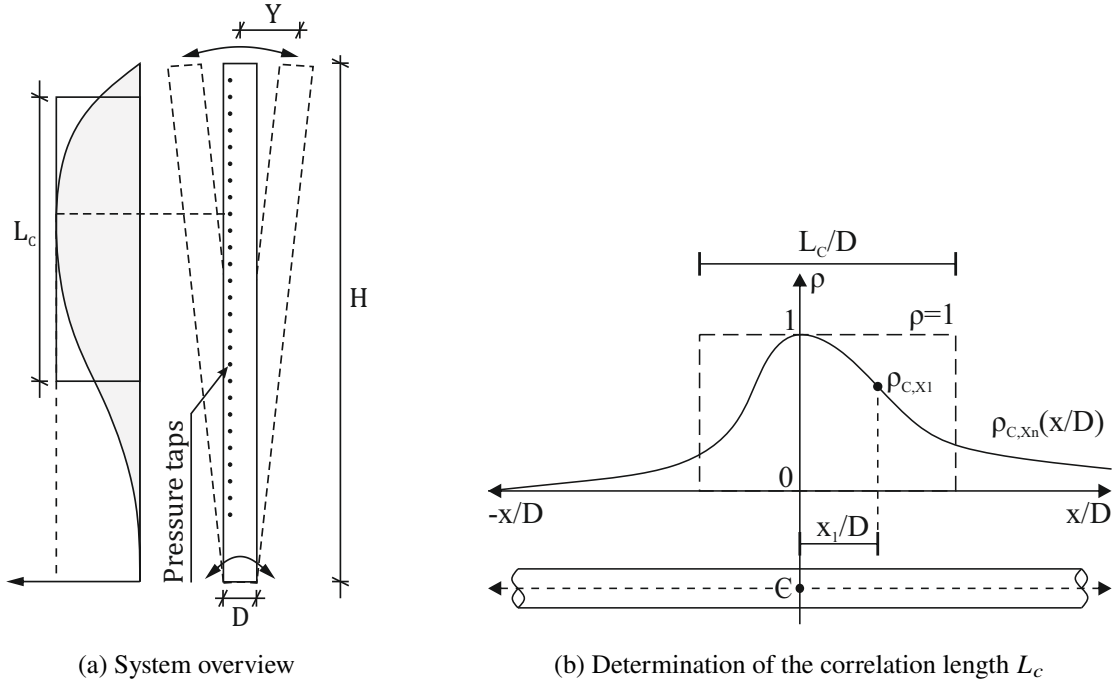


Figure 1: (a) Schematic of the test setup showing the oscillating cylinder with vertically distributed pressure taps used for spanwise correlation analysis. (b) Definition of the correlation length L_c derived from the spatial decay of the cross-correlation coefficient ρ along the normalized coordinate x/D .

2.3 Aeroelastic measurements

To complement and validate the forced-oscillation results, aeroelastic free-vibration tests were conducted in the same facility using the same BLS configurations with increasing wind speeds. For these tests, a lighter and low-damped tower model was needed to ensure VIV excitability. Therefore, a lightweight carbon-fiber model with identical outer geometry ($D = 50$ mm, $\lambda = 25$) was built. The structural stiffness was adjusted by a flat spring between tower base and the connector plate of the massive foundation block. With this set-up, a Scruton number $Sc \approx 2$ and a natural pivoting frequency around $f_n \approx 8.5$ Hz was achieved. The model contained 7 pressure taps positioned at heights corresponding to a subset of the 21 taps of the forced-oscillation model.

Figure 2 shows the oscillation amplitudes (a) and the normalized correlation lengths (b) for the different BLS with growing v/v_{crit} . The aeroelastic oscillation amplitudes in Figure 2 (a) are reported as the equivalent sinusoidal amplitude $Y_{eq} = \sqrt{2} Y_{rms}$, where Y_{rms} is the root-mean-square of the tip displacement. For a purely harmonic signal, this expression recovers the peak amplitude exactly. Since the aeroelastic response is a narrow-band random process with time-varying amplitude, Y_{eq} provides a single representative value that is directly comparable to the constant displacement amplitude Y imposed in the forced-oscillation tests. This equivalence holds well within the lock-in range, where the response is quasi-harmonic; outside resonance, the signal becomes broadband and Y_{eq} is less meaningful as a physical amplitude but is retained here for consistency with the forced-oscillation comparison.

Figure 2 (b) shows the correlation length as calculated in section 3.

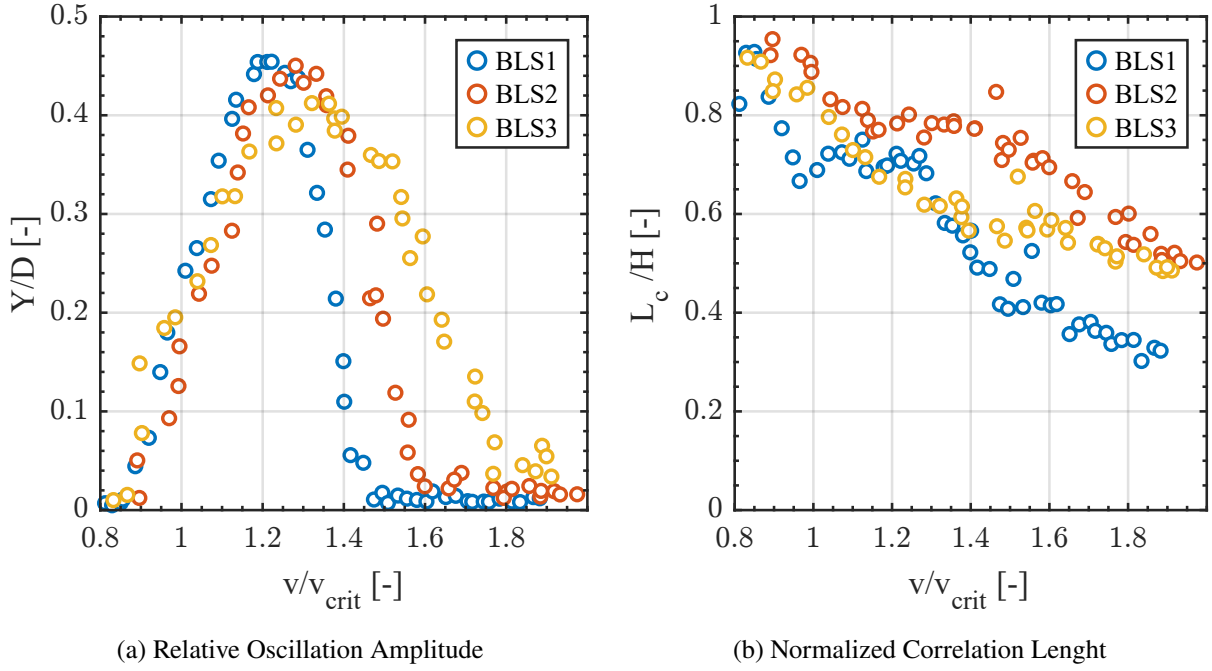


Figure 2: Steady state relative oscillation amplitudes Y/D (a) and normalized correlation lengths L_c/H (b) from aeroelastic tests under different boundary-layer conditions as a function of the velocity ratio v/v_{crit}

3 EVALUATION

The correlation length L_c is determined from the spanwise cross-correlation of surface pressures, following the classical approach of Toebe [2], and Novak and Tanaka [3]. For each pressure tap i , the cross-correlation coefficient $\rho_{c,x_i}(x/D)$ with all other taps along the model height is computed, and the integral of the resulting distribution defines an equivalent fully correlated length L_c (Fig. 1 (b)). The governing correlation length is selected as the one yielding the maximum equivalent base moment.

In the forced-oscillation tests, the imposed harmonic motion dominates the pressure spectrum across the entire v/v_{crit} range. Outside the lock-in region, this leads to artificially elevated spanwise correlations that reflect the imposed motion rather than aerodynamic forcing. The effect is most pronounced at low v/v_{crit} , where vortex-shedding forces are weak relative to the mechanical excitation; at higher wind speeds, the aerodynamic forcing becomes strong enough to produce a distinct correlation signature, and the measured values decrease. A similar phenomenon occurs in the aeroelastic tests: at low wind speeds, broadband structural vibrations dominate and inflate the correlation, while at higher speeds the vortex-shedding contribution differentiates itself and the correlation decreases. Consequently, correlation lengths evaluated outside the lock-in range should be interpreted with caution in both test configurations.

4 RESULTS

Figure 3 shows normalized correlation length curves L_c/H as a function of the relative top oscillation amplitude Y/D for the three boundary layer simulations, and for six v/v_{crit} ratios. The correlation lengths from forced-oscillation tests (*Forced.Osc.*) have been fitted using a cubic smoothing spline (*Forced.Osc.-BLSX(css)*) for better trend visualization.

The forced-oscillation results for the static cylinder yield correlation lengths in the range $L_c/H \approx 0.20$ – 0.50 , with the lower values corresponding to smooth flow (BLS1). With increasing oscillation amplitude, the correlation length grows, reaching plateau values of $L_c/H \approx 0.80$ –

0.90 that decrease with growing v/v_{crit} . The plateau values decay more rapidly in smooth flow (BLS1) than in turbulent conditions (BLS2/BLS3). This effect is attributed to the wind shear profile: when the reference wind speed at tower top exceeds the lock-in range, lower segments of the model still experience near-critical velocities due to the boundary-layer gradient, so that rougher terrain profiles effectively widen the lock-in range along the model height.

Accordingly, the aeroelastic results (Fig. 2) show that while the maximum oscillation amplitudes are comparable across all three boundary-layer simulations, the extent of the lock-in range differs substantially. Under smooth flow (BLS1), the response exhibits a narrow lock-in band centred around $v/v_{\text{crit}} \approx 1.15\text{--}1.20$ with an abrupt stop of oscillations at $v/v_{\text{crit}} \approx 1.35$. This self-limiting behaviour at relatively high v/v_{crit} is consistent with the findings reported by Lupi et al. [6] for cylinders with low Scruton numbers. Under turbulent conditions (BLS2, BLS3), the lock-in range widens progressively. The corresponding correlation lengths (Fig. 2 (b)) follow a decreasing trend with increasing v/v_{crit} , with BLS1 exhibiting the steepest decay. These results indicate that, although peak amplitudes are relatively insensitive to boundary-layer conditions, the width and shape of the lock-in range depend strongly on them. This has direct implications for fatigue assessment: the number of load cycles accumulated over a structural lifetime is governed by the extent of the lock-in range rather than the peak amplitude alone, a parameter not accounted for in current prediction models.

4.1 Comparison of forced-oscillation and aeroelastic results

Figure 3 compares the normalized correlation lengths L_c/H from forced-oscillation and aeroelastic tests. Within the lock-in region ($v/v_{\text{crit}} \approx 1.00\text{--}1.30$), the two methods show good agreement: both exhibit a monotonic increase of L_c/H with Y/D , converging to similar plateau levels around $L_c/H \approx 0.75\text{--}0.85$. This confirms that the forced-oscillation approach adequately reproduces the spanwise coherence of aerodynamic forces under resonant conditions, where the imposed harmonic motion closely resembles the self-excited response.

At velocity ratios outside the lock-in range, systematic deviations emerge. For $v/v_{\text{crit}} \approx 0.90$, the aeroelastic results show elevated correlation lengths ($L_c/H \approx 0.8\text{--}0.9$) at low amplitudes, which reflect the dominance of broadband structural vibrations rather than aerodynamically induced spanwise coherence (see Section 3). For $v/v_{\text{crit}} \geq 1.30$, the aeroelastic data—particularly under turbulent conditions (BLS2)—retain higher correlation lengths than the forced-oscillation curves at comparable amplitudes. This discrepancy arises because the aeroelastic model still sustains flow-structure interaction within its extended lock-in range at these velocity ratios, whereas the forced-oscillation method at the same v/v_{crit} imposes motion at a frequency increasingly mismatched with the vortex-shedding frequency. The forced-oscillation data are therefore most representative of the physical correlation length near $v/v_{\text{crit}} \approx 1.0\text{--}1.3$.

4.2 Comparison with standards and literature

Figure 4 compares the forced-oscillation correlation lengths at $v/v_{\text{crit}} = 1$ with the established curves of Ruscheweyh [1] and Novak and Tanaka [3]. Novak and Tanaka used cross-section models ($\lambda \approx 12$, smooth flow, $Y/D \leq 0.1$) and fitted exponential decay functions to the correlation envelope, resulting in unbounded growth of L_c/D with amplitude. Their curves are steeper than the present data at small amplitudes ($Y/D < 0.1$), which is attributed to their two-dimensional test conditions (no tip effects or boundary-layer shear). Ruscheweyh's design curve, adopted in Eurocode 1, starts at $L_c/D = 6$ and rises only moderately, reaching approximately $L_c/D = 12$ at $Y/D = 0.75$; it does not depend on aspect ratio.

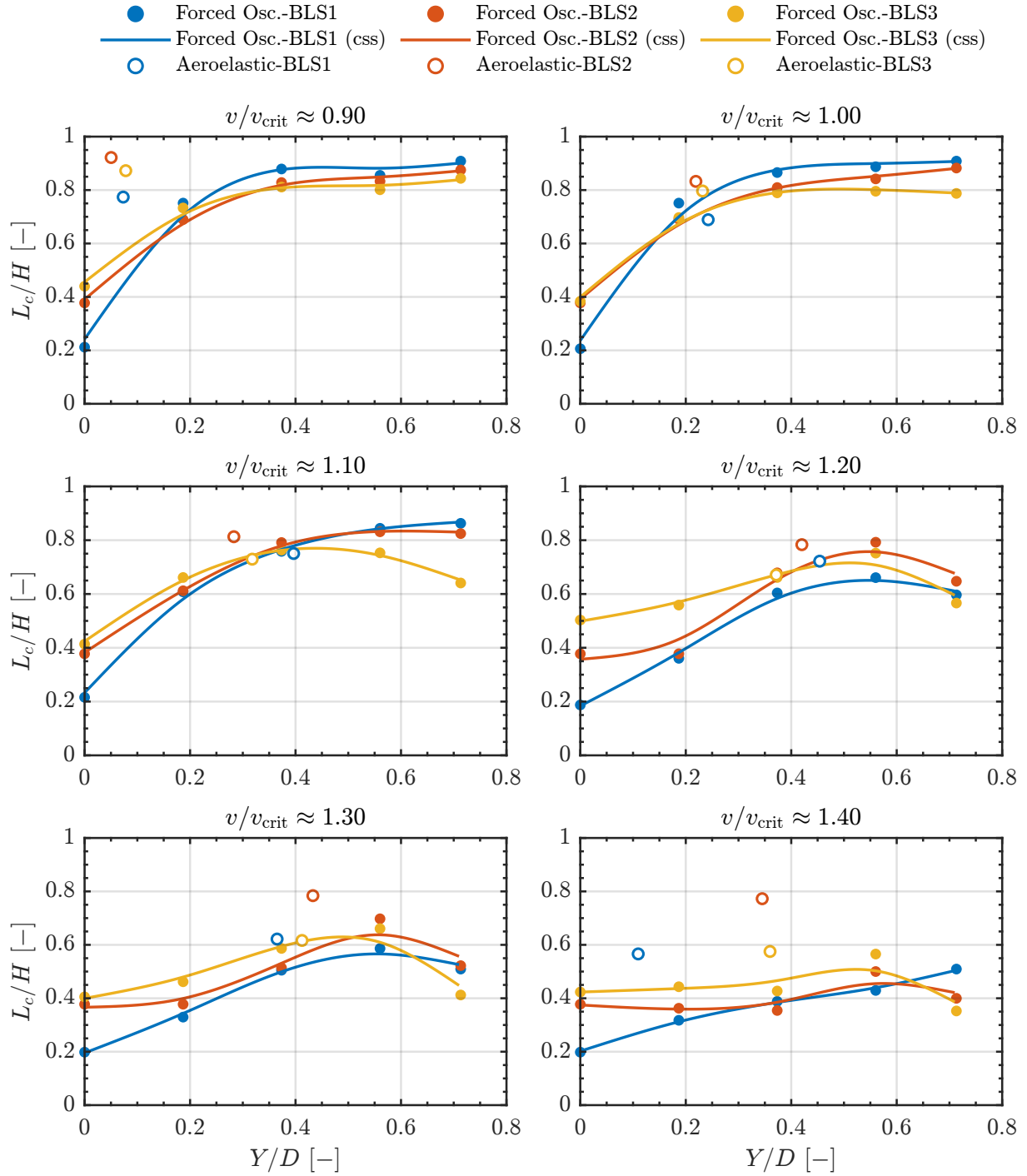


Figure 3: Normalized correlation length L_c/H versus relative oscillation amplitude Y/D for six values of v/v_{crit} . Solid lines with filled markers denote forced-oscillation measurements; open markers denote aeroelastic results. Colors indicate BLS1 (blue), BLS2 (red), and BLS3 (yellow).

The present measurements for $\lambda = 25$ exceed Ruscheweyh's curve across the entire amplitude range. Already in the static case ($Y/D = 0$), the measured values ($L_c/D \approx 9$) exceed Ruscheweyh's starting value. At moderate and large amplitudes ($Y/D > 0.2$), the difference becomes substantial: the measured correlation lengths reach $L_c/D \approx 18$ – 22 depending on the boundary-layer simulation, approximately twice the standard value. This systematic discrepancy is attributable to the high aspect ratio of the test model, which allows spanwise synchronisation

to extend over a larger portion of the structure height. When normalised by the structure height (L_c/H), the correlation lengths for all three BLS collapse into a narrower range, confirming the dominant role of the aspect ratio. In the ECLA, the aerodynamic loading is governed by the product $c_{lat} \cdot L_c$, so that a larger correlation length does not necessarily imply larger predicted amplitudes if the corresponding lift coefficient is lower. Consequently, the measured correlation lengths cannot be applied in isolation: a consistent re-evaluation of c_{lat} under the same experimental conditions and using a methodology compatible with the correlation length determination is required. This combined assessment will be addressed in future measurement campaigns.

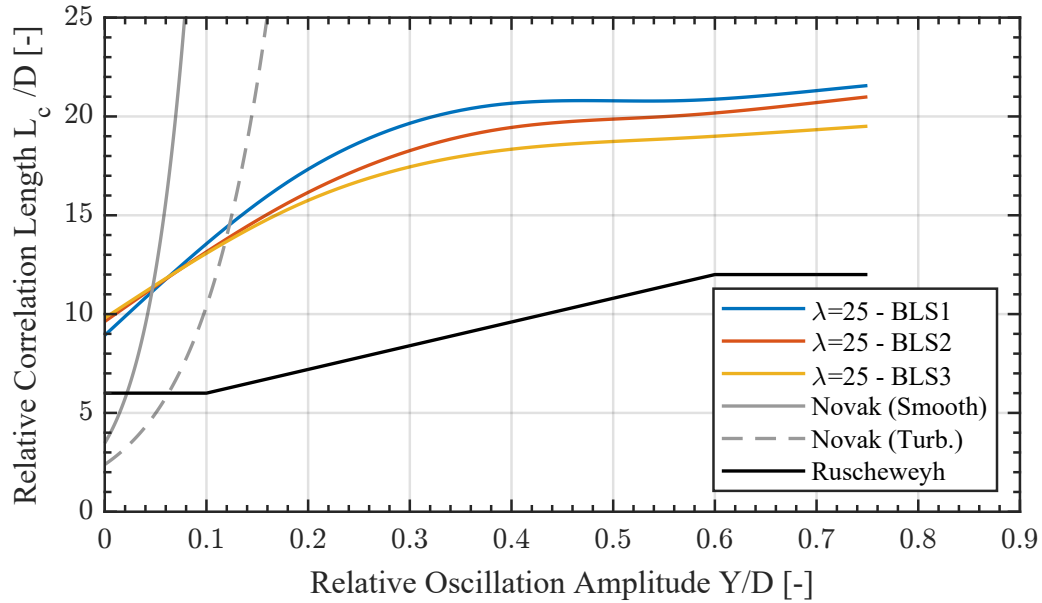


Figure 4: Correlation length L_c/D versus Y/D at $v/v_{crit} = 1$ for $\lambda = 25$ under three BLS, compared with the curves of Novak and Tanaka [3] (smooth and turbulent flow) and Ruscheweyh [1] (Eurocode 1).

5 CONCLUSIONS AND OUTLOOK

Forced-oscillation and aeroelastic wind-tunnel measurements on a circular-cylinder model with $\lambda = 25$ show that the correlation length increases with oscillation amplitude up to plateau values of $L_c/H \approx 0.80$ – 0.90 , significantly exceeding the values prescribed in current standards. Both methods yield consistent correlation lengths within the lock-in range ($v/v_{crit} \approx 1.0$ – 1.3), confirming that the forced-oscillation approach adequately reproduces the aerodynamic spanwise coherence under resonant conditions. The aeroelastic tests further reveal that the width of the lock-in range depends strongly on boundary-layer conditions, with implications for fatigue assessment, as the accumulated load cycles over a structural lifetime are governed by the extent of the lock-in range rather than the peak amplitude alone. Since the ECLA relies on the product $c_{lat} \cdot L_c$, a consistent re-evaluation of both quantities under identical experimental conditions is necessary before the results can be applied for design.

The correlation length evaluation presented here follows the classical integral approach. However, several refinements are under development to address the challenges identified above. Band-pass filtering the pressures around the structural natural frequency yields high correlations at low v/v_{crit} due to the forced or stochastic motion, while filtering around the Strouhal-dependent shedding frequency produces high correlations outside lock-in at frequencies irrelevant for res-

onant VIV. Future work will combine both filtered correlation lengths to identify the onset of lock-in more precisely. Additionally, the spectral energy content will be used as an indicator of resonance conditions, since it increases markedly within the lock-in range. A phase-based decomposition of the pressure signals is also planned, aiming to isolate the components acting in phase with the velocity and against the structural damping—equivalent to identifying negative aerodynamic damping. This would enable the determination of correlation length and force magnitude exclusively from the resonance-exciting pressure components. The evaluation remains challenging due to the single-line sensor arrangement along the model height rather than a distributed array around the cross-section.

The Reynolds numbers in the wind tunnel measurements remain substantially lower than in the full-scale case, a limitation that is inherent to boundary-layer wind tunnels and difficult to overcome at model scale. To address this, full-scale measurements are planned within the SenSPhWT project [7, 8], in which pressure sensors will be installed on a wind turbine tower provided by the industrial partner Nordex SE. The project also includes coupled CFD–multi-body simulations, which—combined with the wind tunnel data—will allow the numerical models to be validated at model-scale Reynolds numbers and subsequently extrapolated to full-scale conditions. This triangulation of wind tunnel experiments, CFD simulations, and full-scale measurements is intended to cover the key uncertainties across the parameter space and to provide a more complete and validated description of the VIV problem for engineering practice.

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