AEROELASTIC AND STRUCTURAL DYNAMICS OF WIND TURBINES: AN OPENFAST-BASED COMPUTATIONAL STUDY

Muhammad Usman SIKANDAR, Kaunas University of Technology, Faculty of Mechanical Engineering & Design, Experimental & Computational Mechanics Research Group, Kaunas, Lithuania / Offshore Wind Learning, London, UK, email: muhsik@ktu.lt
Chris LLOYD, Offshore Wind Learning, London, United Kingdom, info@offshorewindlearning.com
Olga KHRYSTOSLAVENKO, Vilnius Gediminas Technical University, Department of Environmental Protection and Water Engineering, Vilnius, Lithuania, Olga.khrystoslavenko@vilniustech.lt

Abstract

Wind energy has become a critical component of the renewable energy sector, necessitating advanced computational models to enhance wind turbine performance and structural resilience. This study employs OpenFAST, a multi-physics simulation tool developed by NREL, to investigate the aeroelastic and structural dynamics of the onshore configuration of the NREL 5-MW reference wind turbine — a model originally developed for offshore applications but widely used in both onshore and offshore research contexts. The primary objectives include analyzing turbine eigenmodes, assessing power-thrust characteristics, and evaluating blade bending moments under both steady and turbulent wind conditions. Eigenmode analysis reveals significant out-of-plane bending in the first blade mode and coupled bending-torsional motion in the tower, emphasizing the importance of structural optimization. The power curve exhibits a rapid increase up to the rated wind speed of 12–15 m/s, stabilizing due to active pitch control mechanisms that regulate aerodynamic loads. The thrust force peaks at 11-12 m/s, marking a transition in aerodynamic loading before pitch adjustments mitigate further increases. Under turbulent wind conditions, increased fatigue loads and structural oscillations highlight the necessity for robust damping techniques and fatigue-resistant materials to ensure long-term reliability. The results underscore the significance of aeroelastic interactions, and structural flexibility in optimizing wind turbine longevity and operational efficiency. Further research could explore larger-scale systems, such as the openly available IEA 15MW Reference Wind Turbine and their digital twin's development.

Keywords: Wind turbines, Aeroelasticity, OpenFAST, Structural dynamics, Power curve, Fatigue loads, Renewable energy, Digital Twins

Introduction

The global shift towards renewable energy has propelled wind energy to the forefront of sustainable power generation. Wind turbines, particularly large-scale multi-megawatt (MW) models, require advanced computational models to optimize performance, structural integrity, and longevity. The interplay between aerodynamic forces and structural dynamics, commonly referred to as aeroelasticity, is a critical aspect of wind turbine design and operation (Ageze et al., 2017). Aeroelastic modeling of wind turbines is essential for understanding the coupled interactions between fluid flow and structural response. Conventional aeroelastic codes such as Blade Element Momentum (BEM) theory have been widely employed for rotor aerodynamics, while multi-body and finite-element approaches model structural dynamics (Sessarego et al., 2016). However, modern high-fidelity simulations integrate computational fluid dynamics (CFD) with structural solvers to improve accuracy, particularly for large, flexible blades (Della Posta et al., 2021).

OpenFAST, a multi-physics simulation tool developed by the National Renewable Energy Laboratory (NREL), provides a comprehensive platform for analyzing wind turbine dynamics (NREL, n.d.). OpenFAST represents an evolution from the FAST v8 code and serves as an open-source simulation framework for aero-hydro-servo-elastic engineering models of wind turbines. The software includes well-documented source code, automated regression testing, and robust multi-platform build support. It is widely used in research and industry for aerodynamic and structural dynamic performance analysis. NREL's 5 MW offshore reference turbine model, developed in 2009, has been extensively used for validation and aerodynamic studies, making it an essential benchmark for computational simulations.

This study employs OpenFAST to investigate key aeroelastic and structural parameters of a 5 MW onshore wind turbine. The primary objectives include:

- Eigenmode analysis of turbine components to understand structural flexibility.
- Evaluation of power-thrust characteristics over a range of wind speeds.
- Assessment of blade bending moments under steady and turbulent wind conditions.

Recent studies emphasize the importance of robust computational models for predicting aerodynamic loads and structural deformations in real-world operational scenarios. A novel two-way coupling method demonstrated that aeroelastic feedback significantly affects blade dynamics, particularly as the blades pass in front of the tower (Della Posta et al., 2021). Additionally, the introduction of geometrically exact beam formulations has enhanced the accuracy of flutter and fatigue analyses for large wind turbines (Rezaei et al., 2017).

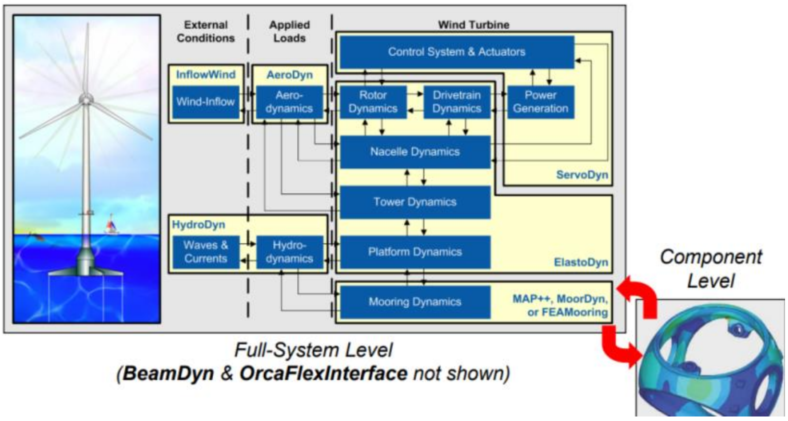

Fig. 1. Simulation framework for floating offshore wind turbines, showing interactions between aerodynamics, hydrodynamics, structural dynamics, and control systems.
1 pav. *Plaukiojančių jūrinių vėjo turbinų modeliavimo sistema, rodanti aerodinamikos, hidrodinamikos, konstrukcijos dinamikos ir valdymo sistemų sąveiką.*

This paper contributes to the field by providing an OpenFAST-based computational analysis that bridges the gap between theoretical predictions and real-world performance. By evaluating eigenmodes, power-thrust curves, and blade bending moments, the study enhances predictive modeling capabilities and informs future wind turbine design improvements. Future research directions may include advanced control strategies, novel composite materials, and real-time operational monitoring to further improve efficiency and durability (Zhu et al., 2020).

Research object and methods

OpenFAST Model Setup

The computational framework for this study utilizes OpenFAST, an advanced open-source multi-physics simulation tool developed by the National Renewable Energy Laboratory (NREL), to analyze the aeroelastic and structural dynamics of the well-established 5 MW reference wind turbine. Although this turbine was originally developed for offshore applications, particularly to support system design studies in the OC3, OC4, and OC5 projects, OpenFAST provides multiple configurable environments that allow the same turbine to be analyzed under land-based (onshore), fixed-bottom offshore, and floating offshore conditions.

These configurations include:

Offshore – Fixed-Bottom Systems:

In this setup, the turbine is supported by a monopile or jacket foundation. The structural behaviour of the substructure is modelled using SubDyn, which accounts for support structure flexibility, while HydroDyn simulates hydrodynamic loading, including wave and current forces acting on submerged components.

Offshore – Floating Systems:

For floating platforms, OpenFAST allows integration of floating support structures such as spar-buoys, semi-submersibles, and tension-leg platforms (TLPs). These are modelled along with mooring systems using either MoorDyn (a dynamic cable model) or MAP++ (a quasi-static or hybrid approach), while HydroDyn handles wave radiation and diffraction effects (using WAMIT).

In this study, however, the turbine is analyzed in a land-based configuration, meaning the simulations exclude hydrodynamic and substructure interactions, focusing solely on the structural and aerodynamic subsystems (i.e., rotor, nacelle, and tower). The simulation setup is tailored to the problem statement objectives and consists of the following three major tasks:

1. Aeroelastic Modeling: Eigenmode analysis of the blade and tower was performed using OpenFAST's structural solvers — ElastoDyn for multibody dynamics and BeamDyn for blade flexibility — to capture natural frequencies and mode shapes. Although not explicitly emphasized, aerodynamic forces were computed via the built-in AeroDyn module, enabling realistic aeroelastic interaction under steady and turbulent wind conditions.
2. Power and Thrust Curves: Simulations were conducted over a wind speed range of 3 m/s to 25 m/s in 2 m/s increments under steady and turbulent conditions to assess aerodynamic performance. Power and thrust outputs were derived using the AeroDyn module, with wind inflow handled by InflowWind, and active pitch control managed by ServoDyn above rated wind speed.
3. Blade Bending Moments: Time-series analysis of in-plane and out-of-plane bending moments was performed for Blade 1 at 11 m/s under both steady and turbulent wind conditions. Aerodynamic loads from AeroDyn were passed to the structural solvers — ElastoDyn and optionally BeamDyn — to resolve the blade's dynamic response.

Simulation Conditions

1. Steady-State Wind: The power and thrust variations were analyzed under steady-state conditions to provide a baseline for turbine performance.
2. Turbulent Wind: TurbSim-generated turbulence was applied to evaluate the dynamic response and fatigue effects of fluctuating aerodynamic loads.
3. Eigenmode Analysis: The natural frequencies and mode shapes of turbine components were computed using OpenFAST's BModes module, ensuring structural flexibility assessment and avoiding resonance risks.

Research results and discussion

Eigenmode Analysis of Blade and Tower

The modal analysis of the NREL 5MW wind turbine was performed to identify the natural frequencies and deformation patterns of both the blades and tower under dynamic conditions.

Figure 2 illustrates the out-of-plane blade mode shapes (flapwise), where each curve represents a distinct mode of vibration (Shapes 1–5). The first out-of-plane mode (Shape 1) shows a smooth, large displacement at the blade tip, highlighting its dominant bending behaviour and vulnerability to aerodynamic excitation. As the mode number increases (Shapes 2 to 5), the curves develop additional nodes (zero-crossings), reflecting higher-order bending modes with increased oscillatory complexity. These higher modes are crucial when assessing the blade's fatigue life, as they indicate susceptibility to resonance with harmonic excitations, especially from turbulent wind and rotor rotation frequencies.

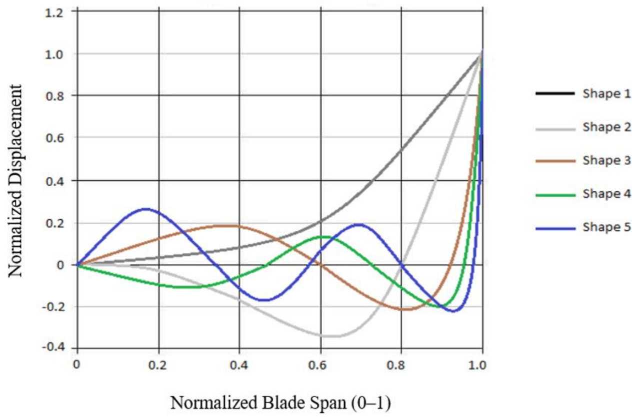

Fig. 2. Out-of-plane mode shapes (Blades)
2 pav. *Neplokštuminio režimo formos (Mentės)*

In contrast, Figure 3 presents the in-plane blade mode shapes, also from Shape 1 to Shape 5. The in-plane first mode again demonstrates tip displacement, but along the rotational plane, making it more relevant to edgewise vibrations. The increasing number of nodes in higher shapes reflects complex in-plane dynamics, which become particularly relevant during yaw misalignment or operational gusts.

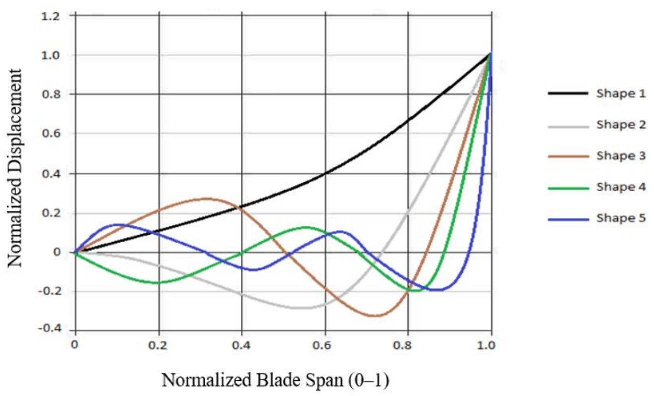

Fig. 3. In plane mode shapes (Blades)
3 pav. *Formos plokštumoje (Mentės)*

Figure 4 focuses on the tower mode shapes, which also exhibit increased complexity with higher modes. The first tower mode shows a gentle, global bend — typical of a cantilevered structure under lateral loading. However, Shapes 2 through 5 demonstrate multiple inflection points, suggesting localized bending or wave-like deformation along the tower height.

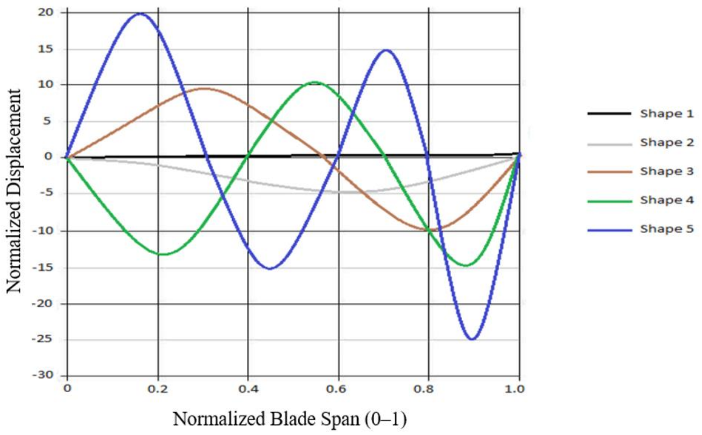

Fig. 4. Mode shapes (Tower)
4 pav. *Režimo formos (Bokštas)*

Power and Thrust Performance Under Steady Wind

The power curve (Fig.5a) of the turbine follows the expected trend, where power output increases proportionally with wind speed until reaching the rated power of approximately 5 MW at 12-15 m/s.

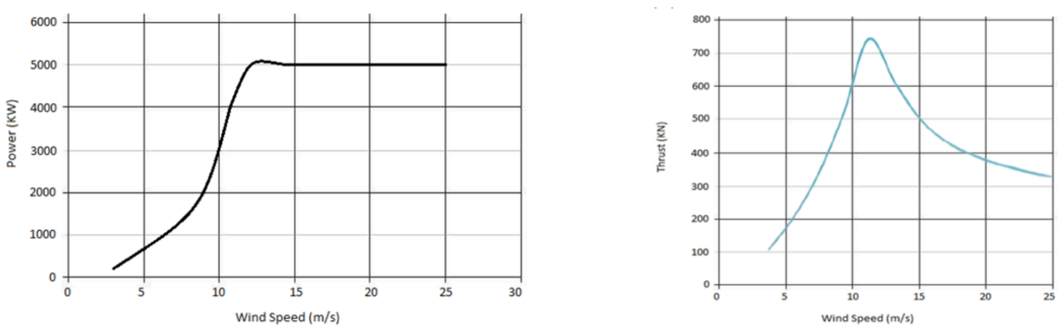

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Fig. 5. Power & Thrust Curve
5 pav. *Galios ir traukos kreivė*

Beyond this point, power remains constant due to the activation of blade pitch control mechanisms, which regulate aerodynamic efficiency to prevent excessive loads on the structure. The thrust curve (Fig. 5b) exhibits a peak of around 11-12 m/s, reflecting the point of maximum aerodynamic force exerted on the rotor before control mechanisms begin to limit the load. The subsequent decline in thrust at higher wind speeds indicates successful regulation strategies, such as pitch control and active yaw adjustments, that prevent excessive structural stress.

Dynamic Structural Response and Bending Moments

The time series of blade bending moments under steady and turbulent wind conditions reveal significant insights into the dynamic behaviour of the wind turbine. Under steady wind conditions (Fig.6), the out-of-plane bending moment shows periodic oscillations, primarily influenced by aerodynamic loading from the rotor's rotation. In contrast, the in-plane bending moment exhibits a higher frequency oscillatory pattern, likely resulting from blade-tower interactions and inertial effects due to centrifugal forces.

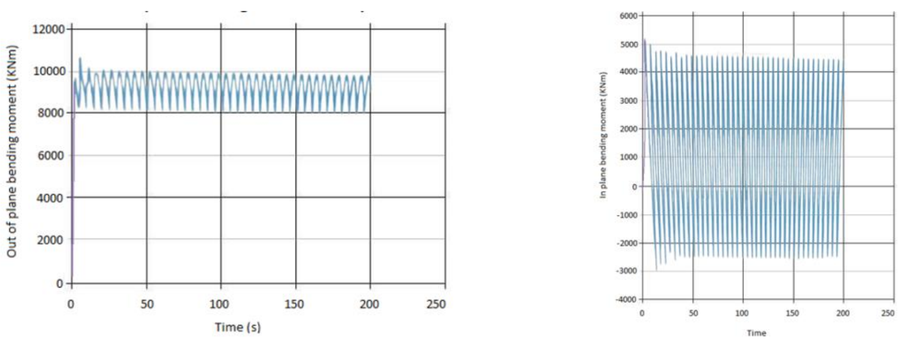

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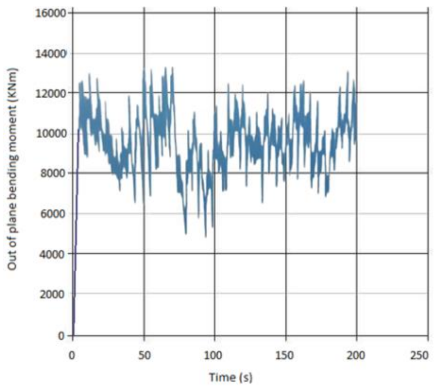
Fig. 6. Out of plane & In-plane bending moment (Steady Wind)
6 pav. *Iš plokštumos ir plokštumoje esantis lenkimo momentas (pastovus vėjas)*

Under turbulent wind conditions (Fig.7), the bending moments show significantly larger fluctuations, indicating unsteady aerodynamic forces acting on the blade and tower structure.



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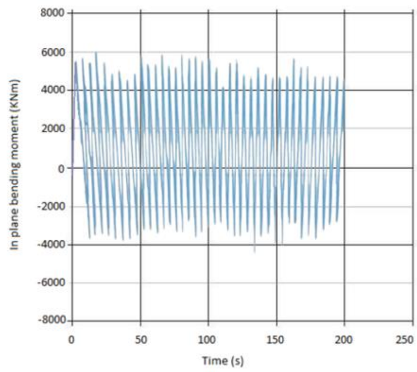

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Fig. 7. Out of plane & In-plane bending moment (Turbulent Wind)
7 pav. *Iš plokštumos ir plokštumoje esantis lenkimo momentas (turbulentinis vėjas)*

The out-of-plane bending moment experiences a broader range of variations due to the stochastic nature of wind turbulence, with occasional peaks suggesting sudden gust loads. Meanwhile, the in-plane bending moment demonstrates an increased high-frequency oscillation pattern, highlighting the importance of transient load analysis in turbine design. The presence of these fluctuations shows room of improvement via robust control strategies and advanced materials that can withstand fatigue-induced damage over the turbine's operational lifespan.

Impact on Structural and Aerodynamic Design

The findings from this study highlight the interplay between aerodynamic loading, structural response, and control mechanisms in large-scale wind turbines. The results underscore the necessity for optimizing blade geometry and material composition to reduce dynamic loads and enhance structural resilience. Furthermore, the bending moment fluctuations under turbulent wind conditions stress the importance of implementing advanced damping techniques, such as tuned mass dampers or active pitch control, to minimize fatigue-induced failures.

In summary, this analysis provides crucial insights into the structural dynamics and aerodynamic efficiency of wind turbines under various wind conditions. The results emphasize the need for continuous improvements in turbine design, considering both aerodynamic performance and structural durability, to ensure sustainable and efficient energy generation in real-world operational environments.

While this study uses OpenFAST as a high-fidelity tool for aeroelastic analysis, transitioning toward a full digital twin requires additional capabilities such as real-time data ingestion, adaptive modeling, and integration with turbine control systems. Digital twins go beyond predictive simulations—they dynamically synchronize with sensor data to support real-time monitoring, fault detection, and maintenance planning. Models like the NREL 5MW and IEA 15MW RWT provide strong physics-based foundations, and ongoing efforts by IEA Wind Task 43 (2020) , NREL's Twin Peak (2021), and DTU's ROM FAST (2019) & digital twin research at TU Delft are actively advancing digital twin development. Building on these, a digital twin for large-scale turbines should incorporate the elements summarized below.

Table 1. Key Components for Wind Turbine Digital Twin Development
1 lentelė. *Pagrindiniai vėjo turbinų skaitmeninio dvynių kūrimo komponentai*

Component	Description / Purpose	Current Efforts / Examples
Physics-based core	High-fidelity OpenFAST model of turbine dynamics	NREL 5MW, IEA 15MW models used in IEA Task 43, DTU studies
Sensor integration	Use of SCADA, Lidar, strain gauges, nacelle accelerometers	Vestas & SGRE platforms, DTU WindScanner
Real-time data pipeline	Live data streaming from turbine systems to model	IEA Task 43 developing data integration frameworks
State estimation	Kalman filtering, digital observers, or ML to update model states in real time	Applied in DTU ROM-FAST project, IEA Task 43 pilot cases
Degradation modeling	Tracking of material fatigue, erosion, and wear	NREL fatigue tracking via rainflow methods; DTU ML fatigue
Control system linkage	Two-way communication with turbine controller for predictive control	Used in Simulink-OpenFAST co-simulations; ROSCO integration
Surrogate modeling	Reduced-order or ML models to enable real-time speed and scalability	ROMs in DTU Wind Energy; ML surrogates in EU-funded projects

Conclusions

This study presents a comprehensive analysis of the dynamic behaviour of the NREL 5MW wind turbine, focusing on eigenmode characteristics, power-thrust performance, and structural response under steady and turbulent wind conditions. The mode shape analysis provides valuable insights into blade and tower deformation, highlighting the significance of avoiding resonance and optimizing material selection. The power and thrust curves exhibit expected trends, with the rated power achieved at approximately 12-15 m/s and thrust peaking around 11-12 m/s before control mechanisms regulate aerodynamic forces. The bending moment analysis underscores the critical role of transient wind effects, demonstrating how turbulence induces higher structural loads and fatigue stresses. These findings reinforce the necessity for robust turbine design, incorporating advanced damping strategies, aerodynamic optimization, and real-time control mechanisms to enhance performance and durability. Further research could explore novel materials, and hybrid damping mechanisms to further improve wind turbine resilience and could extend the analysis to larger-scale systems, such as the openly available IEA 15MW Reference Wind Turbine and their digital twin development. This would enable deeper investigation into next-generation turbine dynamics across both offshore and onshore applications.

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References

1. Ageze, M. B., Hu, Y., & Wu, H. (2017). Wind turbine aeroelastic modeling: Basics and cutting edge trends. *International Journal of Aerospace Engineering*, 2017, 1-15. https://doi.org/10.1155/2017/5263897
2. Della Posta, G., Ciri, U., Leonardi, S., & Bernardini, M. (2021). A novel two-way coupling method for the study of the aeroelasticity of wind turbines in a Large Eddy Simulation framework. *14th European Conference on Turbomachinery Fluid Dynamics and Thermodynamics*. https://doi.org/10.29008/etc2021-696
3. National Renewable Energy Laboratory (NREL). (n.d.). OpenFAST Documentation. National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/wind/nwtc/openfast.html
4. Rezaei, M., Behzad, M., Haddadpour, H., & Moradi, H. (2017). Aeroelastic analysis of a rotating wind turbine blade using a geometrically exact formulation. *Nonlinear Dynamics*, 89, 2367-2392. https://doi.org/10.1007/S11071-017-3591-1
5. Sessarego, M., Shen, W., Sørensen, J., & García, N. R. (2016). *Design of large wind turbines using fluid-structure coupling technique*. Technical University of Denmark. https://backend.orbit.dtu.dk/ws/files/132539494/PhD_thesis_DTU_Sessarego.pdf
6. Zhu, J., Ni, X., & Shen, X. (2020). Aerodynamic and structural optimization of wind turbine blade with static aeroelastic effects. *International Journal of Low-carbon Technologies*, 15, 55-64. https://doi.org/10.1093/ijlct/ctz057