Mitteilung

Fachgruppe: Aerodynamik bodengebundener Fahrzeuge

Wind tunnel calibration methodology for measuring aerodynamic loads on operational high-speed trains

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A reduced-scale wind-tunnel experimental methodology is presented that provides calibration and insight for measurements on an operational high-speed train; the Deutsche Bahn advanced TrainLab (aTL, Figure 1a) [1]. A 5-hole dynamic pressure probe mounted at the front of the aTL is used to determine the incoming flow magnitude and direction. A 1:10 scale wind-tunnel experiment was performed to determine probe corrections to remove the local effects on the probe of the train's head on the incoming flow. A 1:25 scale wind-tunnel experiment was performed to determine drag, side-force and lift polars for the 1st carriage of the aTL (Figure 1b,c). The corrected probe measurements and force calibration provide quasi-steady force estimations (length-scales ≈ train length) of the aTL under real-world operation. A belt of 9 surface-pressure taps around the circumference near the front of the aTL provides insight into the unsteady (length-scales ≪ train length) pressure and forces operational high-speed trains experience. The surface pressure was measured at these locations in both scaled wind-tunnel experiments and at two further positions along the length of the body as well as on the nose of the models for additional insight into the causal flow physics and potential for surface-pressure measurements on operational high-speed trains in the future.

This work is part of the joint project 'KI-MeZIS - AI Methods in Condition Monitoring and Demand-Adapted Maintenance of Rail Vehicle Structures' coordinated by DB AG with the partners DB InfraGO AG, DB AG's AI Factory, DB Systemtechnik, Industrial Analytics GmbH, University of Stuttgart, Institut für Bahntechnik GmbH, MSG Ammendorf and DLR. The project is supported by the BMWK technical programme 'New Vehicle and System Technology', within the framework 'Artificial Intelligence as a Key Technology for the Vehicle of the Future'. The aim of this project is to develop and use an AI-based, onboard monitoring system for operational rolling stock to detect, measure and analyse impact or run-over events as well as aerodynamic loads [1,2]. The output of the monitoring system will be used for strategic maintenance as well as needs-based, cost and energy efficient design of future rolling stock [2].

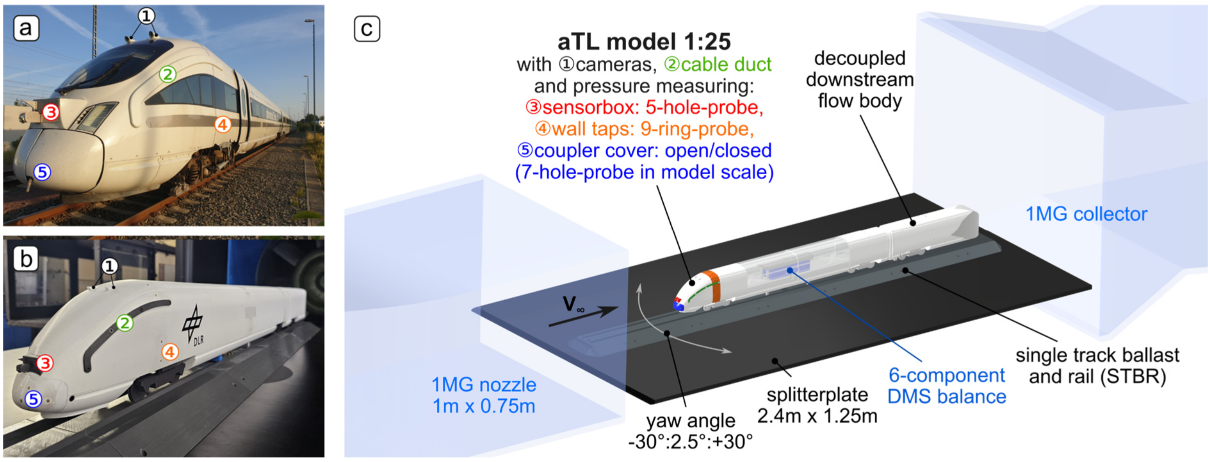

Figure 1: a) advanced TrainLab with sensor systems, b) 3D-printed, 1:25 scale model and c) 1:25 scale setup as measured in the one-metre low-speed wind tunnel Göttingen (1MG).

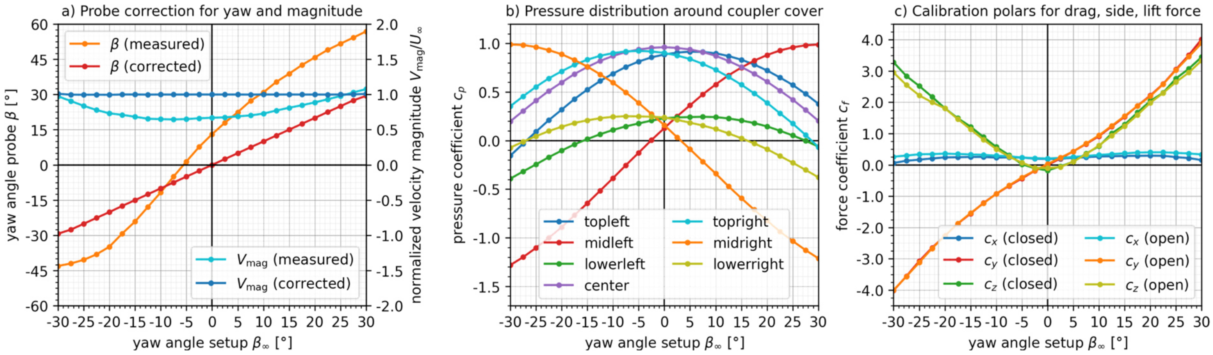

Figure 2: a) measured and corrected probe data for yaw angle and velocity magnitude, b) pressure distribution around coupler cover and c) calibration polars for drag, side and lift force.

The experiments were performed in the one-metre low-speed wind tunnel Göttingen (Figure 1c) at 40m/s wind speed, which corresponds to $Re_h > 10^6$ and respectively $Re_h > 0.4 \times 10^6$ for the 1:10 and 1:25 scale model (related to model height). For each model configuration a yaw angle sweep from -30° to 30° in 2.5° steps was measured. Local effects of specific geometry components of the aTL such as cable duct, sensor box, closed/open coupler cover (Figure 1), were investigated to develop a level of confidence for the robustness for the calibration measurements. The 5-hole probe, the surface pressure taps of the 9-hole belts and 7 additional pressure taps at the coupler cover as well as the total und static pressure of a Prandtl probe in the test section were connected to a 64-channel, 20" WC PSI scanner. The 1:25 scale model was mounted on a 6-component strain-gauge balance (RUAG 196-6I) to measure drag, side and lift forces on the first carriage. The benchmark measurements for the aerodynamic coefficients were performed with reference to the 'Requirements and test procedures for cross wind assessment' (DIN EN 14067-6:2018).

In Figure 2a the correction functions of the 5-hole probe are presented, with measured yaw angle β (orange) and velocity magnitude V_{mag} (cyan), normalized with the freestream wind tunnel velocity U_∞, against the set-up yaw angle β_∞ of the model in the test section. The flow angle $\beta_\infty \leftrightarrow \beta$ and magnitude $\beta_\infty \leftrightarrow V_{mag}$ relationships are not linear due to changing flow displacement around the aTL head geometry for different yaw angles. Neither are symmetric around 0° yaw due to the off-center position of the 5-hole probe to the right side of the aTL nose (Figure 1a,b). Thus, a correction function was derived to determine the 'true' incoming flow conditions β_∞ (red) and U_∞ (blue), which were controlled in the wind tunnel setup. An alternative correction function was determined to be used when the train was operating with an open coupler cover. In Figure 2b the pressure signals of the 7 coupler cover taps are presented. They exhibit changing characteristics with the yaw angle (symmetric to 0° yaw). This indicates that surface pressure taps on the nose region could be a promising alternative to the 5-hole probe. In Figure 2c the drag, side and lift force-coefficient (c_x, c_y, c_z) calibration polars of the aTL's 1st carriage are presented for closed and open coupler cover configurations. For post-processing the full-scale measurements, the probe correction functions are applied to the probe data to determine the oncoming, free-stream (cross-)wind. The force calibration polars are then used to calculate the global aerodynamic loads on the aTL. Within the KI-MeZIS project, the presented results were merged to a database from strain gauge and accelerometer sensor measurements on single aTL surface positions to perform a load spectrum analysis [3]. This analysis can be used to optimize the design and dimensioning of structural components with regard to the required service life or maintenance intervals [2]. The presented methodology could also be used in future high-speed train operation for real-time prediction of aerodynamic loads. This could inform a driver assistance or autonomous system to achieve optimized aerodynamic operation; for improved efficiency and safety.

[1] Digitale Schiene Deutschland, 'Digital Impact Detection in Railway Operations Collecting data for driverless driving - a ride with the advanced TrainLab', https://digitale-schiene-deutschland.de/en/news/2024/DigitalImpactDetection (25/06/2024).
[2] Matthias Härter et al., 'KI-MeZIS: Nutzung von künstlicher Intelligenz für die Zustandsüberwachung von Schienenfahrzeugen', 20. Internationale Schienenfahrzeugtagung, Dresden, 18.-20.09.2024.
[3] Mathilde Laporte et al., 'Methode zur Ermittlung von Betriebslasten bei Schienenfahrzeugen mittels KI-Methoden', 20. Internationale Schienenfahrzeugtagung, Dresden, 18.-20.09.2024.