CFD ANALYSIS ON THE AERODYNAMIC CHARACTERISTICS AROUND A NEXT-GENERATION HIGH-SPEED TRAIN SUBJECTED TO CROSSWIND

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I dedicate my research works to my parents and family members for their unending prayers and encouragement throughout the study period.

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ABSTRACT

The development of Next-Generation High-Speed Trains (NG-HST) made of lightweight materials is a challenging task for the transport industry. With the increasing speed and decreasing structural mass of high-speed trains, it raises concerns about the effects of strong crosswinds on their aerodynamics and train stability. Understanding the aerodynamic characteristics is a requirement for train operational safety analysis of the high-speed train under sudden crosswind. Thus, the goal of this thesis is to investigate the aerodynamic loads and unsteady flow structure around a NG-HST subjected to crosswind using computational fluid dynamics (CFD) analysis. A hybrid Detached eddy simulation (DES) was used to resolve incompressible flow around the train. Based on the height of the train model and freestream velocity, the Reynolds number (*Re*) for the simulation was 1.3×10^6. The simulation was run in different conditions such as crosswind angles of 15°, 30°, 45° and 60°, no crosswind, six *Re*, and steady and transient crosswind. Later, the simulation was compared with the wind tunnel from the previous study for validation purposes. In the results, according to power spectral density (PSD) analysis, increasing the *Re* increased the turbulence intensity of the wake, which gradually dissipated as the distance from the train increased. In terms of transient responses, even low-velocity wind had a very high impact on the aerodynamic loads of the NG-HST. For example, C_s value changes were 166%, 183%, and 190% higher during transient loads for 15m/s, 25m/s, and 35m/s, respectively, compared to normal conditions. In addition, the C_l and C_s with C_{roll} and C_{pitch} provide a strong justification for the running safety subjected to transient crosswind. On the other hand, the vortex structure formation is relatively complex and unsteady at 13° yaw angles for transient as compared to the vortex formation observed for the steady crosswind. The findings of the study may be used to better understand the flow characteristics in the wake of NG-HSTs for future development.

ABSTRAK

Pembangunan *Next-Generation High-Speed Trains (NG-HST)* yang diperbuat daripada bahan ringan adalah suatu cabaran bagi industri pengangkutan. Dengan peningkatan kelajuan dan penurunan jisim struktur keretapi berkelajuan tinggi, sebaliknya, menimbulkan kebimbangan mengenai kesan angin lintang yang kencang terhadap aerodinamik dan kestabilan keretapi. Memahami ciri-ciri aerodinamik diperlukan untuk menjalankan analisis keselamatan operasi keretapi berkelajuan tinggi di bawah angin lintang yang mengejut. Hasilnya, matlamat tesis ini adalah untuk menyiasat beban aerodinamik dan struktur aliran udara di sekeliling NG-HST yang dikenakan angin lintang menggunakan analisis *Computational fluid dynamics (CFD).* Hibrid *detached eddy simulation (DES)* digunakan untuk menyelesaikan aliran tak mampat di sekeliling keretapi. Berdasarkan ketinggian model kereta api dan halaju aliran bebas, nombor *Reynolds (Re)* untuk simulasi ialah 1.3×10^6. Simulasi dijalankan dalam beberapa keadaan yang berbeza seperti sudut angin lintang 15°, 30°, 45° dan 60°, tiada angin lintang, enam *Re*, angin lintang malar dan sementara. Kemudian, keputusan dibandingkan dengan data terowong angin daripada kajian lepas untuk tujuan pengesahan. Menurut analisis *power spectral density (PSD)*, dengan meningkatnya *Re*, ia akan meningkatkan keamatan turbulensi bangun, yang secara beransur-ansur hilang apabila jarak dari keretapi meningkat Dari segi tindak balas sementara, angin halaju rendah pun mempunyai kesan yang sangat tinggi terhadap beban aerodinamik *NG-HST*. Selain itu, C_l dan C_s (166%, 183%, dan 190% lebih tinggi semasa angin sementara) dengan C_{roll} dan C_{pitch} memberikan justifikasi yang kukuh untuk keselamatan operasi keretapi yang tertakluk kepada angin lintang sementara. Pembentukan struktur pusaran adalah agak kompleks dan tidak tetap pada sudut angin lintang 13° untuk keadaan angin sementara, berbanding angin lintang yang berterusan. Dapatan kajian boleh digunakan untuk lebih memahami ciri-ciri aliran susulan *NG-HST* untuk pembangunan masa hadapan.

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LIST OF SYMBOLS AND ABBREVIATIONS

AIAA	-	American Institute of Aeronautics and Astronautics
ASME	-	American Society of Mechanical Engineers
C_d	-	Drag coefficient
CFD	-	Computational Fluid dynamics
C_l	-	Lift coefficient
C_p	-	Pressure coefficient
C_{pitch}	-	Pitching moment
C_{roll}	-	Rolling moment
C_s	-	Side force coefficient
C_{yaw}	-	Yawing moment
DDES	-	Delayed detached eddy simulation
DES	-	Detached eddy simulation
DLR	-	German aerospace center
GCI	-	Grid convergence index
GIT	-	Grid independent test
HST	-	High-Speed Train
LES	-	Large eddy simulation
NG-HST	-	Next-Generation High-Speed Train
NGT	-	Next-Generation Train
RANS	-	Reynolds-Averaged Navier-Stokes
Re	-	Reynolds number
RE	-	Richardson extrapolation
RT	-	Regional Train
TSI	-	Technical Specifications for Interoperability

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CHAPTER 1

INTRODUCTION

1.1 Research background

In many countries around the world, high-speed trains (HSTs) are regarded as a quick, safe, and comfortable mode of transportation [1]–[3]. HSTs would be far more efficient and cost-effective than air or automobiles for trips of 100-1000 km, yielding significant cost, fuel, and time savings. Consequently, the demand for this mode of transportation has been increasing rapidly in recent years. Though, there are a number of issues that may cause concern in the coming years [4]. These issues are including a reduction in carbon emissions, extreme weather events, climate change and the demand for high-speed and lightweight structures for vehicles (Figure 1.1).

There will be rising demand for a reduction in carbon-based transportation energy usage, both due to supply concerns and the need to reduce carbon production to counteract the effects of climate change [4]. Secondly, climate change will have an increasing impact on transportation networks, particularly in terms of the frequency of extreme weather events. Finally, vehicles will become lighter as new materials are developed with higher speeds. This shows the future challenges and opportunities in the development of the railway industry.

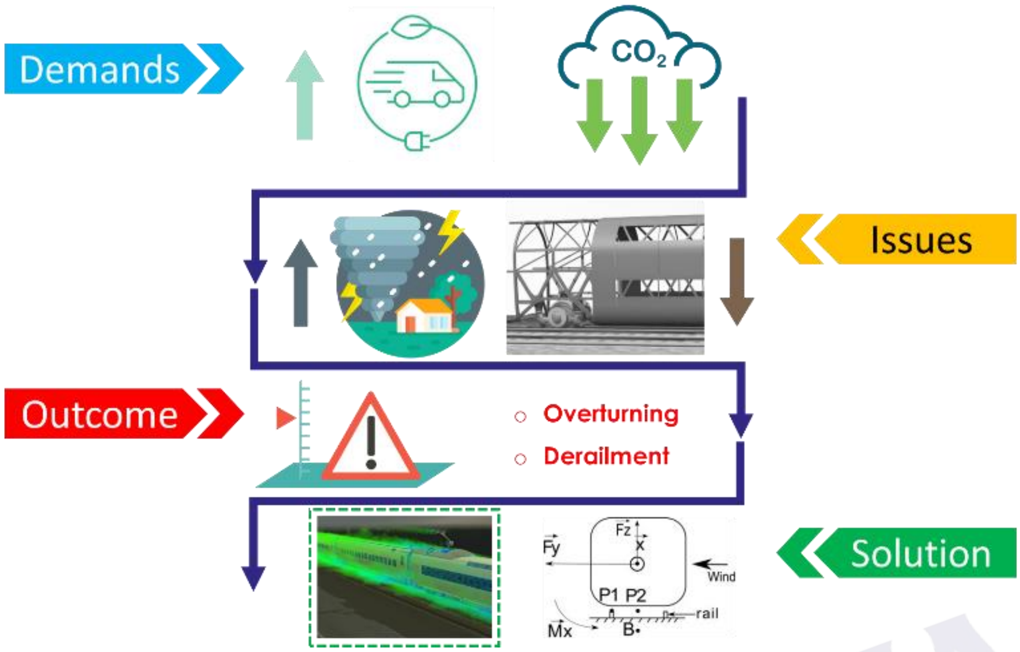

Figure 1.1: Overview of the background study

More research must be conducted from both a technical and non-technical perspective to address the issues that have arisen regarding the future development of high-speed train transportation, Currently, the development of next-generation high-speed trains (NG-HST) made of lightweight materials is a challenging issue for the train transportation industry. Lightweight trains minimize axle loads, which saves money by lowering rail track maintenance costs and the energy required to drive vehicles [5], [6]. As a result, travel time can be significantly reduced, and the train can operate at optimum efficiency [7].

However, the increasing speed and decreasing mass of HSTs, on the other hand, raises concerns about the effects of extreme weather events such as sudden wind on their aerodynamics and train stability. It is especially significant when there is a strong crosswind [8]. Figure 1.2 depicts some train accidents due to overturning under crosswind conditions. Although such accidents are uncommon, they show the possibility and relevance of knowledge of the unsteady flow structures and the resulting acting forces on the surface of the trains. In addition, understanding the aerodynamic characteristics is a requirement for running a safety analysis of the NG-HST under transient crosswinds.

Figure 1.2: Examples of train accidents caused by strong crosswinds [9], [10]

There are several techniques available for understanding the aerodynamic performance of a high-speed train, including full-scale experiments, computational approaches using computers, and physical modeling [11], [12]. Each method has advantages and disadvantages. In particular, the computational fluid dynamics (CFD) technique has gained popularity in recent years due to its ability to calculate full fluid flow around the train, velocities, and pressures. It is anticipated that CFD capabilities at a level of reliability are sufficient to eliminate the need for physical model tests in many areas.

A number of suitable modeling approaches are generally used, including steady and unsteady Reynolds-Averaged Navier–Stokes (RANS) techniques, large eddy simulation (LES), and detached eddy simulation (DES) to study the aerodynamic performance, including aerodynamic loads and flow characteristics of the trains. RANS models are widely used in train aerodynamics to study a variety of problems, but they are unable to calculate where there is a very large unsteady condition [13]. On the other hand, LES can predict instantaneous flow characteristics and resolve turbulent flow structures [14], whereas RANS methods provide averaged results. However, LES is computationally expensive as it solves all the large eddies. At this point, one of the promising solutions is DES which was proposed by Spalart in 1997 [15]. When compared to RANS, DES improves accuracy when massive separation exists, but at a lower computational cost than LES.

The ongoing development of NG-HST, HST, and regional trains (RT) with moderate to high operating speeds, particularly for intercity transport, has quickly become the highlight of alternative public transportation technology. At the same time, safety is also becoming an issue for this industry. A comparison among three types of trains is shown in Table 1.1. The main differences are speed, weight in terms of structure, and the noise generated by the train. This refers to the advantages of next-generation trains.

Table 1.1: Comparison of different types of train

Characteristics	NG-HST [16]	HST [17]	RT [17]
Speed	More than 400 km/h	Varies between 250 to 350 km/h	Between 100 km/h 200 km/h
Coach length	20m	Up to 27m	Up to 25m
Passenger capacity	79/coach	55/coach	Up to 120
Weight (Structure)	Light	Moderate	Heavy
Power source	Inductive power transfer from the track to receivers distributed over the length of the train	Electric power from overhead wires, using a pantograph	Diesel
Noise	Less Noise as no pantograph	Moderate	High
Wheel system	Two single-wheel pairs per coaches	Double wheel pairs	Double wheel pairs
Energy	Energy efficient	-	-
Coupling Function	Remote, contactless coupling functionality	Scharfenberg coupler	Varies

Some recent studies has been conducted on the simplified model of NG-HST in terms of flow over the train [18], crosswind stability on the front car and a partial section of the middle car [19], performance of different turbulence models [20], transient pressure around HST [21], and the effect of steady crosswind [22] and so on. The results showed the formation of a large vortex system at the leeward side of the train, which primarily causes the overturning force and moment. Furthermore, the laminar flow at the train's nose would convert to a fully turbulent flow in the wake zone. It has also been discovered that crosswind situations cause an increase in pressure on the windward side. Force coefficients, on the other hand, increase with both wind speed and train speed, though the change is not linear in a steady crosswind.

A preliminary review of the literature reveals that a very small number of research has been conducted on the NG-HST trains. It implies the importance of performing thorough research on the aerodynamic performance of NG-HSTs subjected to crosswind conditions in order to improve their crosswind stability.

1.2 Problem statement

The development of new materials introduced lightweight structural designs for different railway applications. The lightweight structure of the NG-HST reduces axle loads, which saves money by lowering rail track maintenance costs and the amount of energy needed to drive vehicles. On the other hand, the issue of sudden extreme weather events is becoming unpredictable due to climate change. Climate change-induced increases in the intensity and frequency of extreme weather events can have a significant influence on railway networks. As a result, increasing speed to reduce travel time and the lightweight structural design of the NG-HST raises concerns about the effects of crosswinds on train aerodynamics.

A strong wind gust (also referred to as transient crosswind) can result in a large unsteady flow structure around a moving train, resulting in sudden changes in aerodynamic forces when wind speed changes with respect to time. Wind-induced derailment becomes more likely as train speed and vehicle area profile normal to wind direction increase. Moreover, the increased height (as the train double-deck type) adds a significant lateral force increase and the resulting rolling moment to the other associated issues such as forces on the surface [23]. Even different wind conditions are important factors in determining the risk of a train overturning and derailment [24].

Wind gusts are naturally diverse in terms of shape, frequency, features, and intensity, and can be classified as deterministic or stochastic. However, they are typically idealized as deterministic gusts, which are then layered into wind turbulent oscillations [25]. A deterministic wind gust is a variation in wind velocity that is specified by a simple, generally mathematical, function of time. This type of fluctuation happens in the same direction as the longitudinal gust [26]. It was discovered that side force is mostly determined by upstream wind velocity fluctuations [27] and lift coefficient by free-stream turbulence level [28]. This demonstrates the transient response of wind gusts on vehicles' aerodynamic forces.

A number of research has been undertaken to understand the flow structure around HST under crosswind conditions. The details can be found in the ref. [12],

[29]–[32]. Due to the difficulties of simulating transient winds, they commonly simulated their cases using a crosswind at a steady wind velocity. However, in reality, the wind velocity varies significantly and is obviously not constant or steady as mentioned earlier. Thus, it is one of the aspects that need to be investigated whether or not steady wind loads are feasible to get accurate aerodynamic forces and flow structures.

Moreover, the flow structure at the wake has significant effects on the trackside workers, passengers and nearby infrastructure. There are a number of parameters that affect the flow structure at the wake, *Re* is one of them. Nowadays most of the research on the aerodynamics of HSTs uses a scaled model to reduce the computational cost, which results in a much lower *Re* than the corresponding full-scale test. If *Re* is large enough the effect on the aerodynamic parameters is relatively small, but it is often difficult in the scaled model test. With the unique shape and when operating at a different speed, there may be some unclear differences. As a result, it is essential to investigate the effects on the wake flow structure in different *Re*.

The above discussion also demonstrates the necessity of constructing a thorough aerodynamic characterization and understanding of the factors that influence how the flow around an NG-HST evolves. In addition, a comparison between the effects of different types of wind loads on train aerodynamics should be considered.

1.3 Research objectives

The overall aim of the study is to investigate the aerodynamic performance around a next-generation high-speed train subjected to transient crosswind conditions using CFD analysis. The following are the objectives of this research:

(i) To examine the effects of different Reynolds numbers on the flow structure

(ii) To investigate the aerodynamic characteristics and time-dependent flow physics around the NG-HST subjected to transient crosswind

(iii) To analyze the effects of steady and transient crosswind conditions on the aerodynamic performance

1.4 Research scope

The current research concentrated on the following activities:

(i) A numerical study was carried out using DES on a simplified NG-HST model with three cars (front, middle, and rear) to compare it to the original version of the train [33].

(ii) All the simulations were run in static condition as moving condition has negligible impact on the aerodynamic loads and overall flow structure [34].

(iii) Based on the height of the train model and freestream velocity, the Reynolds number (*Re*) for the simulation was 1.3×10^6.

(iv) The aerodynamic forces considered were forces: drag, lift and side; and moments: rolling, yawing and pitching.

(v) To understand the effects of different *Re*, six *Re* ranging from 7.42×10^5 to 1.62×10^6 were used to examine the characteristics of vortex structures, streamline distributions, velocity characteristics, and pressure characteristics in the wake region of an NG-HST.

(vi) Three simplified wind velocity profiles were considered to simulate the transient wind with the maximum velocity of 15 m/s, 25 m/s, and 35 m/s, respectively.

(vii) To understand the aerodynamic characteristics, four crosswind angles were considered based on ref. [35] i.e. 15°, 30°, 45° and 60°.

(viii) For the grid independence study, Richardson extrapolation and the grid convergence index were utilized.

(ix) For validation, the aerodynamic load was compared with wind tunnel data from the German Aerospace Centre (DLR) [36].

Figure 1.3 represents the scope of the current research, which focuses on the aerodynamic characteristics of a NG-HST. Among other extreme weather conditions, the influence of crosswind on the NG-HST has been studied and investigated using CFD simulation and the simulation was validated using a previous study.

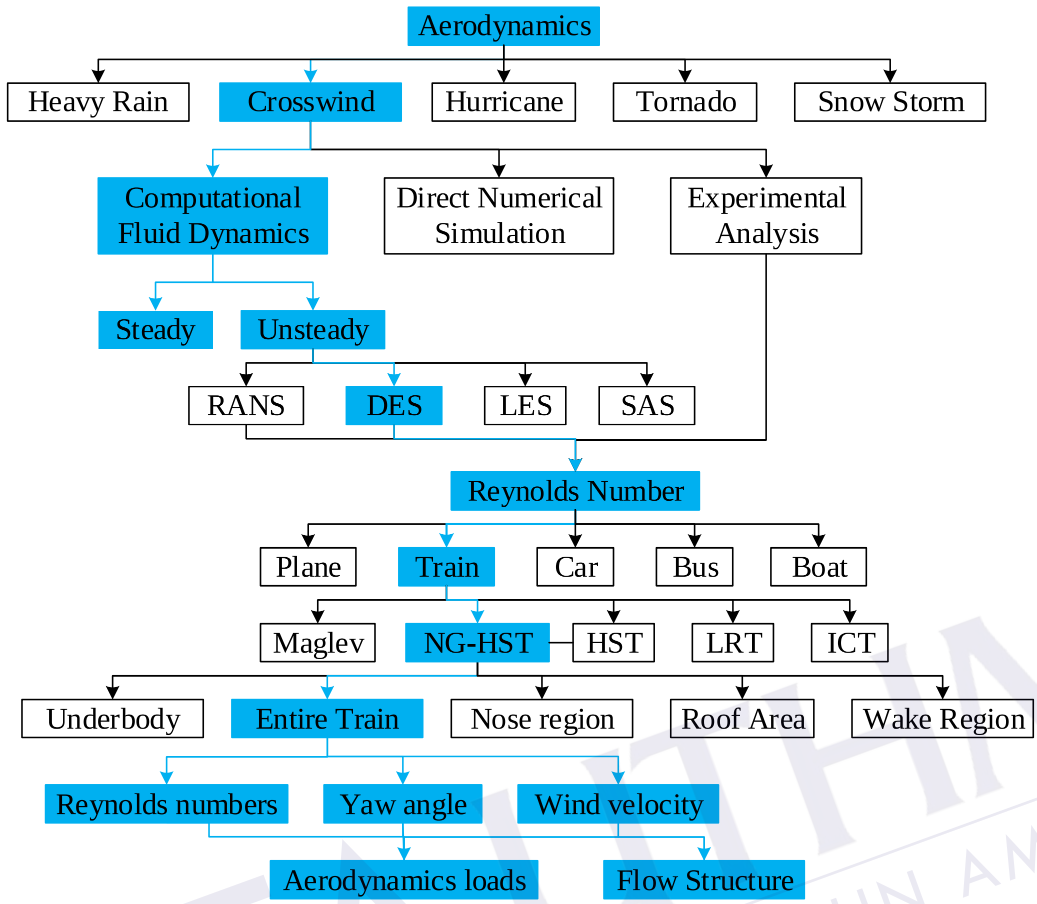

Figure 1.3: An overview of the current study's research scope

1.5 Significance of the study

(i) The proposed study will provide an inclusive analysis of flow physics, highlighting different characteristics of flow behavior and occurrences with respect to the two flow regimes (i.e., the lower degree of yaw angle and the higher degree of yaw angle) near a train vehicle under the influence of the crosswind.

(ii) The research findings are expected to fill gaps in the scope of the train vehicle study. Aerodynamic forces are one of the two stages of achieving safety guidelines for train operation. Information on the aerodynamic forces obtained from simulation results may provide valuable technical information to the community, particularly the railway industry.

(iii) The current NG-HST research will contribute to a better understanding of the flow field under the influence of transient crosswinds. The expected outcome

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APPENDIX A

List of Publication

(i) **Arafat, Mohammad** and Ishak, Izuan Amin. "CFD Analysis of the Flow around Simplified Next-Generation Train Subjected to Crosswinds at Low Yaw Angles." *CFD Letters*. 14, 3 (Apr. 2022), 129–139. https://doi.org/10.37934/cfdl.14.3.129139 [**Scopus**]

(ii) **Arafat, Mohammad**, Ishak, Izuan Amin and Ahmad, Faiz Muhammad. "Effect of Reynolds number on the wake of a Next-Generation High-Speed Train using CFD analysis." (2022). Accepted for International Conference on Computational Heat Transfer and Fluid Mechanics, Kuala Lumpur, Malaysia [**Scopus**]

(iii) **Arafat, Mohammad**, Ishak, Izuan Amin and Ahmad, Faiz Muhammad. "Influence of mesh refinement on the accuracy of numerical results for Next-Generation High-Speed Train." (2022). **Under review** at *IOP Engineering research express* [**Web of Science**]

(iv) **Arafat, Mohammad** and Ishak, Izuan Amin. "Investigation of sudden wind loads on the aerodynamics of Next-Generation High-Speed Train." (2022). **In preparation** for the *Journal of wind engineering and industrial aerodynamics* [**Web of Science**]

VITA

The author was born in February 19, 1996, in Rajshahi, Bangladesh. He went to Masjid Mission Academy (School & College), Rajshahi, Bangladesh for his secondary school. He pursued his bachelor degree at Telkom University, Indonesia with a full-scholarship amount of 28 thousand USD, and graduated with a Bachelor in Industrial Engineering in 2019 with The Most Outstanding Graduate Award. During his bachelor, he worked as a teaching assistant for the Engineering Mechanics course. Upon graduation, he then enrolled at the Zhejiang Sci-Tech University, China, in 2019 with full-Scholarship from the Chinese Government, where he completed full coursework consisting of 33 credits with an average score of 88 out of 100 in Mechanical Engineering in 2021, due to covid-19 pandemic he left china without finishing his thesis. Thereafter, he started a Master in Engineering Technology by research at Universiti Tun Hussein Onn Malaysia in 2022. During his bachelor and master studies, he worked actively involved in academic and non-academic societies. He was a research assistant with the Inspira Automation Research Laboratory during his bachelor degree, he was also a member of the Advanced Intelligent Manufacturing Laboratory, Zhejiang Province, China. Before coming to Malaysia, he has publish several scientific articles including in Scopus and Web of Science indexed journals. He participated in several international competitions and received international awards. He is a member of the Industrial engineering and operation research organization (IEOM) and the International association of engineers. He is an expert in SolidWorks, Ansys, Abaqus, Simscale and Matlab. He is a certified SolidWorks associate.