



Aerodynamic design of JR300X frontal shape by computational fluid dynamics

K. Ishizu^a & J. Miyakawa^b

^a*Rolling Stock Department, Shinkansen Operations Division, Central Japan Railway Company, Marunouchi 1-6-5, Chiyoda, Tokyo, Japan*

^b*Nagoya Aerospace Systems, Mitsubishi Heavy Industries Limited, Ohe 10, Minato, Nagoya, Japan*

Abstract

This paper describes the aerodynamic design process of the frontal shape for JR300X, which is the prototype of the next generation high speed train by CJR (Central Japan Railway) aiming for the operational speed of 350 kilometers per hour. The first step is to analyze the flow field around the existing JR300-series frontal shape by the CFD (Computational Fluid Dynamics) technology. Based on the physical knowledge of the flow field, the conceptual design follows to create the candidate frontal shapes. The geometry is improved by the wind tunnel test as the next step. The candidate shapes are then quantitatively evaluated by CFD under the actual operating condition. The noise measurement test is also conducted at the anechoic wind tunnel to evaluate the acoustic characteristics. The final shape of "CUSP" is selected as the JR300X frontal shape, which is confirmed to perform low drag and low noise characteristics.

1 Introduction

Central Japan Railway (CJR) has been operating Tokaido Shinkansen service between Tokyo and Osaka. The train service was initiated in 1964 and will be celebrated for its thirtieth anniversary in this October. Annual passengers are more than a hundred million in recent years, and the total passengers summed up to 2.8 billion by the end of March 1994. The maximum operating speed was 210 kilometers per hour initially, and was increased to 225 kilometers per hour in 1986 and further increased to 270 kilometers per hour by the introduction of the 300-series train in 1992. The development of the 300X-



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series (JR300X) was started in 1990 in order to study on the ideal next generation high speed train system with the projected maximum operating speed of 350 kilometers per hour. This technology is also considered to be applied to the future Chuo Shinkansen service, which is regarded as the second Tokaido Shinkansen, connecting Tokyo, Nagoya and Osaka. This high speed operating condition imposes some aerodynamic challenges, such as aerodynamic drag, aeroacoustics noise, tail car stability and micro pressure wave propagation in tunnels. As far as the frontal shape of the new bullet train is concerned, it has to provide low aerodynamic drag and low aeroacoustics noise, as a nose car. The noise consideration is one of the major priority tasks for the train service along the heavily populated area with the strict noise regulation. It also has to create stable wake flow, as a tail car, in order not to induce tail swing instability. The conventional tool to attack these aerodynamic tasks is wind tunnel testing. The CFD technology with supercomputers, on the other hand, has been matured to be a practical tool to analyze these various aerodynamic train situations in a short period of time.

This paper describes the design process of the frontal shape for the next generation high speed train. The design study assumes that the shape with low aerodynamic drag should also achieve low aerodynamic noise because of its less separation and less vortical flow. The assumption turns out to be valid as the result of this design study. First, the conceptual design is described, and the wind tunnel testing is then outlined. Performance evaluation by the CFD analysis and the corresponding geometry improvement is next discussed. Noise test for the acoustic characteristics evaluation is finally explained for the aerodynamic configuration completion.

2 Conceptual Design

The first step of the configuration development is to understand the flow mechanism around the frontal shape of the high speed train. In order to probe the flow field, the existing JR300-series frontal shape is analyzed by the CFD technology.

The CFD technology is the advanced aerodynamic software on supercomputers to provide the detailed information on the flow field for the profound aerodynamic understanding. The CFD technology has been developed in aerospace community for aerodynamic configuration design. The actual CFD system applied to this aerodynamic design is the one developed at Mitsubishi Nagoya, which has been developed as a practical tool to design aerodynamic shape for various aerospace vehicles.1),2) The CFD technology consists of four technical elements, geometry definition, grid generation, flow solver and post processing. The geometry definition is to create the exact mathematical modeling to represent the geometry to be evaluated. The grid generation is to discretize the three-dimensional space around the geometry into a system of grid points in order to solve the flow field equations. The flow solver is to solve the air flow governing equations, or the Navier-Stokes

equations based on the finite difference scheme. The post processing is to extract the meaningful engineering results from the numerous amount of digital data. The CFD system has been validated with the aerospace experimental data, such as wind tunnel data and flight data, to have high accuracy in predicting the flow field around the flying vehicles and the related aerodynamic performances. In order to apply the advanced technology to the flow field of the high speed train, several modifications are made preceding to the current design study. The CFD code is then validated to the surface pressure data obtained in the field test of the existing JR300-series frontal shape to ensure the analytical accuracy.

The result of CFD analysis of JR300-series frontal shape is visualized in the form of surface pressure distribution for the nose car condition.(Figure 1) High pressure area is clearly displayed at the nose tip of the shape, because the air stream directly impinges on this portion of the shape. This implies that the surface slope of this area should have large impact on the aerodynamic drag and possibly aerodynamic noise. Another significant flow phenomenon is captured near the shoulder corner of the shape, where the airflow experiences rather steep pressure gradient. This unfavorable pressure recovery is due to the large curvature of the corner, and it may induce the boundary layer separation and the associated vortical flow. Low pressure region is also seen toward the end of the frontal shape. This additional suction may jeopardize the stability of the thickening boundary layer. Another result of CFD analysis is visualized in the form of particle traces for the tail car condition.(Figure 2) A pair of counter rotating vortices is clearly captured in the wake of the tail car. This vortical flow is the potential source of the tail swing instability. The pair of vortices is due to the low pressure system and the sharp pressure recovery on the tail car surface.

The CFD analysis of JR300-series frontal shape brings two design guidelines that are regarded as important for the frontal shape design. The first issue is that the design object is not the geometrical shape but the pressure field. The aerospace experiences recommend the pressure design because air flow is directly determined by the pressure field. This leads to the importance of not only the aerodynamic forces of candidate shapes but also their pressure field data and flow visualization at the configuration evaluation. The second issue is that major attention has to be paid to the smooth air flow in the area of the nose tip, the shoulder corner and the far end of the frontal shape.

A wide variety of candidate frontal shapes are produced as the results of the conceptual design phase, being based on the CFD analysis of JR300-series frontal shape.(Figure 3) The first category is the series of the conventional shapes, which include the existing JR high speed trains. The second category is the air flow design shapes, which are designed to bring the airflow to certain direction, such as to upward, to sideways and to all directions. The third category is the cusp shapes, which has S-shape line in their cross sections.

3 Wind Tunnel Test



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The next step of the configuration development is the wind tunnel test. The purpose of this physical simulation is twofold. The first purpose is to understand the physics of the airflow around the frontal shape of high speed train. It is true that the laboratory test does not exactly simulate the actual train circumstances, such as the viscous effects and the relative motion of the train to the ground, but still it provides important information of the flow physics. The physical simulation utilizes real air, unlike the digital CFD technology, and the laboratory permits rather free access to flow field in terms of measurements and visualization. The second purpose of the test is to improve the candidate geometry based on the revealed physics of the test results. Some of the models are made of clay so that they are modified or totally reshaped in the course of the experiment.

The wind tunnel test is conducted at Mitsubishi Nagoya Low Speed Wind Tunnel. The tunnel has an octagonal test section with 1.8m height and 2.0m width.(Figure 4) The facility has been mostly used for aerospace vehicle developments, so that the testing technology, such as the model support system and the force measurement apparatus, is sophisticated enough to measure only a small difference in aerodynamic drag coefficient. The ground plate is set up to create fresh boundary layer. The distance between the ground plate and the model is a little larger than the scaled actual distance to account for the difference in the boundary layer thickness. The model scale is 3.3% and more than a dozen of frontal shape models are fabricated with the common center body. The configurations are the results of the preceding conceptual design phase. Each candidate model is attached in front of, as well as at the back of, the center body train to simulate the nose and tail car situations respectively. The model is supported by the thin plate strut at the bottom. The strut is attached to the ground plate and to the balance system underneath. This thin plate is effective in order to minimize the disturbance to the airflow. Measurements are made for three components of aerodynamic force and for flow visualization by oil and tufts. The free stream velocity is 50 meters per second and the corresponding test Reynolds number is 2.9 million based on the length of the frontal shape.

There are three major learning aspects from the wind tunnel test. The first learning is that the air flow design shape to upward does not perform well. This shape has constant streamwise contour across the train spanwise direction, so that it has to employ shoulder corner lines. These corner lines with large curvature induce separation and vortical flow for nose car and tail car condition. The second learning is that the cusp shapes perform better than the other shapes. The S-line section turns out to be effective in smoothly alternating the flow direction. The last learning is that the nose tip is better located high off the ground by roughly one third of the train height. The shapes with their nose located at the bottom require the large flow shift which creates larger aerodynamic drag and more vortical flow. The candidate shapes

are modified based on the learning and fed to the next step of performance analysis by CFD.

4 CFD Evaluation

The CFD technology provides the quantitative comparison of the candidate shapes.(Figure 5) Even though the comparison chart is shown for all the candidate geometry simultaneously in one chart, the actual design process is that of the step by step method with cuts and tries improvement of the candidate shapes. In other words, the preceding computational result is immediately fed back to the design process for geometry refinement. This is another merit to use the CFD technology in developing aerodynamic geometry with high quality in a short period of time.

The CFD analysis results show that the two-dimensional shape has poor performances, as the wind tunnel test shows, in spite of the difference in the moving ground condition and the simulated Reynolds number. This is because the separation from the shoulder edge line is rather insensitive to the relative motion and the Reynolds number effects. The results also show that better performance is achieved by the cusp shapes. The best performance is achieved by the Double Cusp Nose Up which is the shape with the S-shape line in two directions and with its nose shifted upward. It appears that the shape smoothly leads the upcoming flow with the best balance to upward, to sideways and to downward. It is also effective for the tail car condition. Considering the other aerodynamic characteristics, lift and pitching moment, which is related to the aerodynamic stability of the train, Double Cusp Nose Up (or "CUSP") is selected as the best geometry.(Figure 6)

5 Noise Evaluation Test

The final step of the configuration development is the noise evaluation test. The aeroacoustics test is conducted at Mitsubishi Takasago Anechoic Wind Tunnel. The facility has a 30cm square nozzle. The wind tunnel models of 3.3% scale are utilized for this noise test. The model center is placed 75cm distant from the nozzle exit plane with the test air speed of 90 meters per second. Acoustics measurement is made at four different points around the model with quarter inch microphones of frequency band up to 80 kHz. The measured data are reduced by the one third octave band analysis, and the data is further converted to that of the actual operating condition assuming the noise level is proportional to the sixth power of flow velocity. The "CUSP" turns out to be of the best acoustic performance among the test models.

6 Conclusions



The frontal shape of the CJR next generation high speed train prototype is designed by the leading aerospace technology. The first step is to understand the flow mechanism around the frontal shape of the high speed train, with the help of CFD analysis. The second step is to produce a wide variety of candidate frontal shapes based on the physical understanding. The third step is to test the candidate shapes in the low speed wind tunnel to improve the candidate geometry. The next step is to quantitatively evaluate the candidate shapes by the CFD technology with the exact flow simulation. Finally the noise characteristics is evaluated in the anechoic wind tunnel. The "CUSP" shape is selected as the best geometry for CJR next generation high speed train prototype(JR300X).

7 References

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2. Kaiden,T., Ogino,J., and Takanashi,S., "Non-planar Wing Design by Navier-Stokes Inverse Computation," AIAA-92-0285, Jan. 1992.

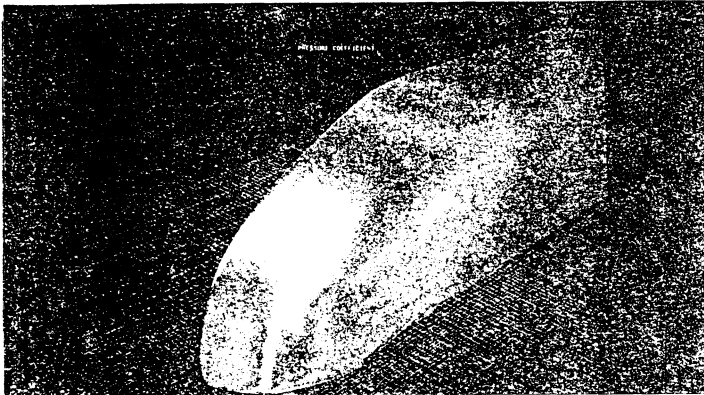


Figure 1 Surface pressure distribution of JR-300 series frontal shape (Nose car condition)

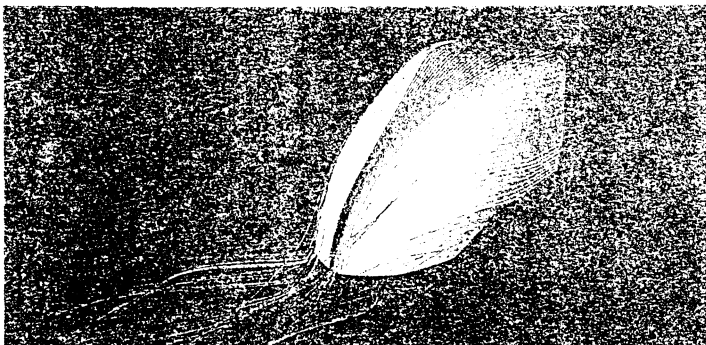


Figure 2 Particle traces of JR-300 series frontal shape (Tail car condition)

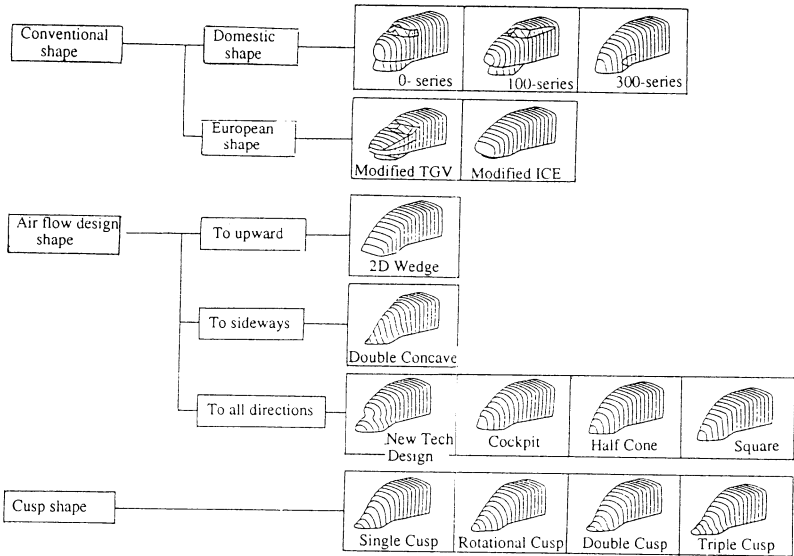


Figure 3 Candidate frontal shapes

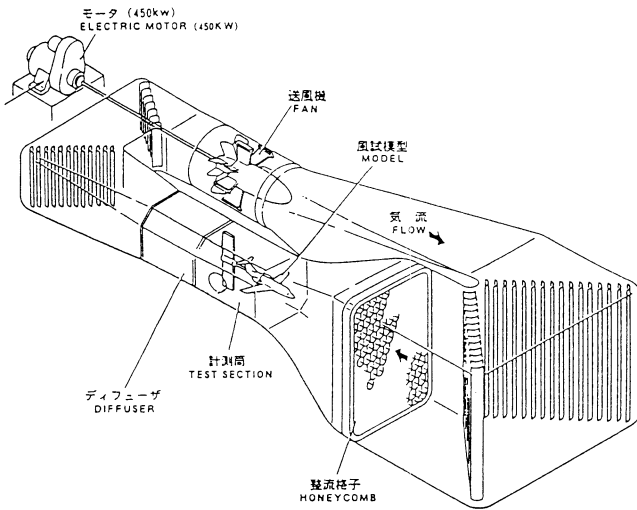


Figure 4 Schematics of Mitsubishi Nagoya Low Speed Wind Tunnel



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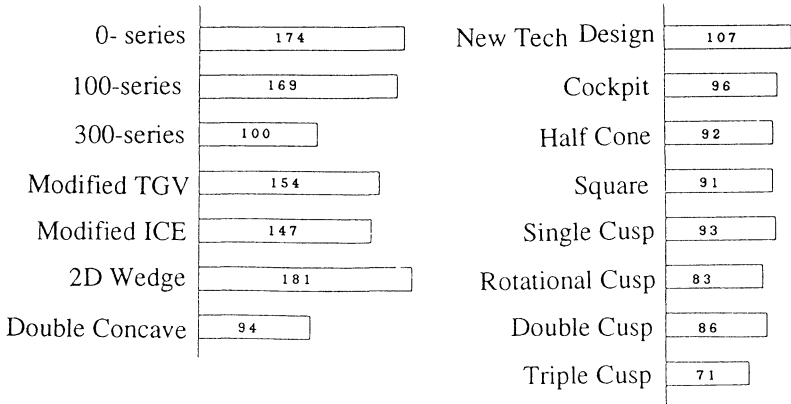


Figure 5 Aerodynamic drag comparison of candidate frontal shapes (in percentage)



Figure 6 Computer graphics image of the CUSP (Double Cusp Nose Up) geometry