How Biomimetic Approach Enlarges Morphological Solution Space in A Streamlined High-speed Train Design?

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ABSTRACT
Ordinarily, high-speed train design methodology has been modeled to guide designer's problem solving and design thinking. However, the current methodology cannot guide designers in very detail due to the reason of the difficulties in bridging gap between pure engineering-knowledge and design-knowledge. In other words, these two knowledge are disconnected each other in a whole frame of design process. But, the paradigm shift that was induced by biomimetic approach has demanded an interdisciplinary approach for a generation of new geometrical characteristics that were impossible to be handled in the current design methodology. In this research, as a case study, we quantify the front-head design of high-speed trains to check the impacts of biomimetic approach. Quantitative methodology of the landmark based morphometric design analysis is introduced and adapted on the study.

KEYWORDS: Biomimetics; Design Analysis; Morphometrics; High-speed Train Design

Introduction

The exterior design methodology of high-speed train takes charge of the development of low resistance vehicle. According to engineering researches, no less than 75% of total resistance is generated by external aerodynamic drag which caused between external vehicle shapes with environmental fluids (Gawthorpe, 1978; Schetz, 2001). In this sense, the relationship between exterior design of vehicle and aerodynamic drag has to be conducted mainly in a high-speed train design (Hucho, 1998). Nevertheless, the current design methodology of high-speed train only supports narrow exterior shape solutions due to its methodological problems. That critical mind has induced the biomimetic approach as a new methodology for complementing this problem. However, the rigorous diagnosis about the limitations of current methodology and the influences of biomimetic approach were not progressed so far.

Specifically, in the current methodology, for the high aerodynamic predictability in exterior shape development, designers have used the 'basic shape' that is composed of two simple parametric splines (Raghunathan et al., 2002). Thus, this current methodology cannot deliver the exterior shape that is composed of complicate features due to the difficulties in numerical prediction. In other words, the current design methodology of high-speed train cannot support much broader solution space that might have superior solutions. Biomimetic approach has made a progress as one methodology for increasing this narrow morphological solution space. Practically by applying bio-models – which were self optimized under their environment – in design problems, engineers can develop the well-qualified design solutions and be possible to expect surmounting preexistence limits (Strove et al., 2009).

In a high-speed train design designers could improve the predictability about the developed shape by using the biomimetic approach. Technically, the adaptation of qualified bio-shape – the shape of life object – has broadened the shape complexity and possibility over the current 'basic shape' modification method has (Stachelberger, 2011). To diagnose the methodological improvements, we can analyze the morphological changes by using quantitative method. As a quantifying method, the morphometric analysis can be used for identifying morphological changes that high-speed train designs have. The morphometrics 'identifies' and 'justifies' morphological characteristics of objects by the numerical data that are defined by landmarks (Parsons et al., 2003). Landmarks based method has an advantage in a morphological object analysis that is composed of detectable parameters. Fortunately, the front-head part of high-speed train is composed of several landmarks that are exposed (Kim, 2008). We expect the landmark based morphometric analysis about serial train designs – designs that were delivered by current methodology and the design that was delivered by biomimetic approach – will practically reveal the physical evidences of the influence that was induced from biomimetic approach.

In this research, we will discuss the impacts of biomimetic approach in design point of view and diagnose practical limitations of the current design methodology with a case analysis about the front-head designs of high-speed train. First we review the current problems that traditional high-speed train design methodology has. Second the serial front-head designs of high-speed train are analyzed quantitatively by using morphometric landmark analysis. Last the morphological changes and characteristics that biomimetic designed vehicle has are discussed.

General High-speed Vehicle Design Process

The three-dimensional streamlined model had replaced the primitive vehicle designs after the First World War (Lichtenstein and Engler, 1995). This innovative movement was induced by aerodynamic researches those attempted at generating an ideal model. The three-dimensional airfoil-like shapes were generated in stream. However, these alternatives could not been an optimal solution due to the engineering and manufacturing constraints and styling issues (Hucho, 1998). Despite of uncertainty of streamlined design alternatives, aerodynamically tested the combination form of profile segments gave a bridging way which addresses designer's 'vague idea' in a reliable design process. Successfully this P. Jaray's 'Combination Form' had induced various style alternatives in market as a design seed; 'basic shape (initial model)'(Fig. 1).

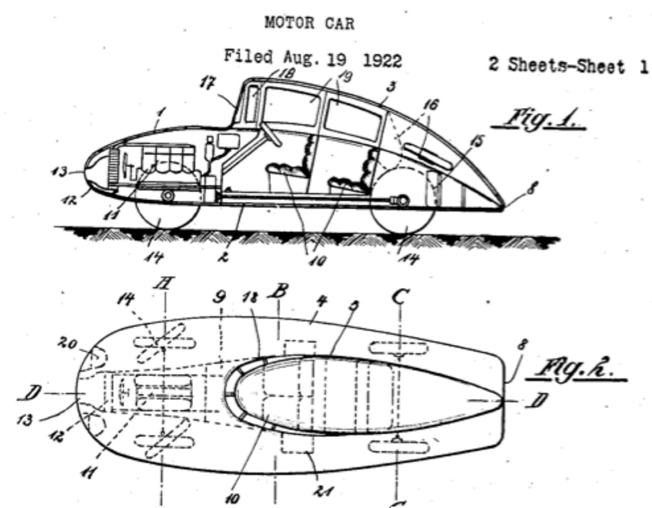


Fig. 1. One Developed Design by the 'Combination Form' of P. Jaray (Jaray, 1927)

In the case of high-speed train design process, the aerodynamic drag has to be important factor for solving the engineering design problem. That's because when the vehicle is driving in high velocity the total resistance causes inappropriate high amount aerodynamic drag. Thus, in the formal design process of high-speed train the influences from exterior design of vehicle should be predicted precisely and as a conclusion of this relationship the low-resistance model should be developed computationally. Practically, however, in the design process that predicting analysis and developing proper exterior model are hardly difficult due to the aerodynamic drag affected by morphological exterior features intricately (Kim et al., 1997).

Ordinarily, in the high-speed train design process the streamlined 'basic shape' has generated by combining two vertical profiles as like as P. Jaray's 'Combination Form'. And the developing process of exterior shape has conducted by controlling numerical parameters that indicated to exponents and coefficients. After that, the developed models were verified by CFD simulation for confirming proper exterior design computationally (Raghunathan et al., 2002; Kim et al., 1997) (Fig. 2).

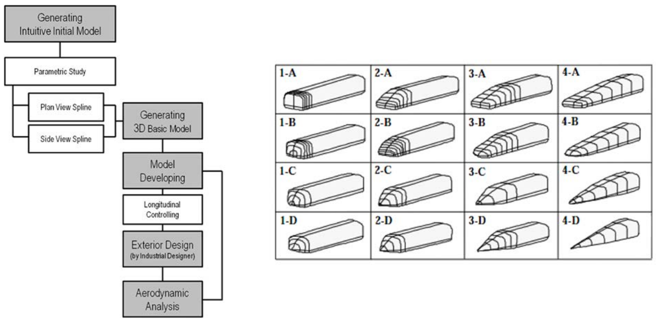


Fig. 2. Current Design Process and Methodology of High-speed Train (Right: Raghunathan et al., 2002)

By doing so, the developed alternative models were roughly categorized by control parameters (Raghunathan et al., 2002), but this process has the limit because it couldn't reflect of many other possibilities that generated by combining with other complex morphological shape features. Indeed, on account of the intricate interrelationship between aerodynamic drag with exterior shape, the unverified model developing is hard to assert as a proper developing method even this model developing method was managed computationally. Practically, after confirming a superior model in developed models is still dependent on other morphological features. As knowledge of engineering, this superiority is easily can be changed when the exterior upper edge or length has interposed or deformed (Kim, I.S. et al. 1997).

Biomimetic Approach in High-speed Train Design

The critical engineering issue – adaptation of biological information on engineering design process – has been discussed in the most bionic researches that were conducted by biomimetics. Historically the biomimetic design had begun to complement the solution generating ability of human being from primitive societies (Dickinson, 1999). Although primitive people did not face as intricate as engineering problems of present, in some manner they also had to overcome the gap between the inspired ideas and design problems. This radical problem is still remained as most critical issue in nature-inspired design activities (Dickinson, 1999). Building a bridge on the gap between nature-inspired ideas and design problems has been conducted in multifaceted ways; including vehicle design work, the problem-oriented cases are spouting from diverse problem-solving domains.

The rate of front-head and tail pressure drag to total aerodynamic drag is about 8~13% (Schetz, 2001). Even the front-head and tail pressure drag is deeply influenced by the front-head and tail exterior shape, but still the exterior shape development process was following simply predictable 'basic shape'. However, the highest driving speed of high-speed train has been increased continuously, and engineers faced the necessity of enhancing the front-head and tail exterior design (Meguru, 2008). In Japan, the research to reduce aerodynamic drag and enhance exterior design had begun earlier than other high-speed train technology nations. By the environmental conditions, most Japanese high-speed railway lines had to be constructed close to densely populated areas, inevitably the high-speed trains are under the strict environmental law. Part of the Japanese pioneer research of *Shinkansen 500 Series* is valuable as the background. This noticeable research of the *500 Series* high-speed train, conducted by *JR West Japan*, showed that using a biomimetic approach, the maximum speed could be improved. This study mimicked a biological model – the bill of a Kingfisher – as a 'basic shape' of the vehicle front-head shape.

Morphometric Shape Analysis

One robust methodology for evaluating shape has been developed by biologists to evaluate and compare bio-models at evolutionary way. This quantifying method was suggested to adapt in 'identification' and 'justification' of morphological variations in the framework of systemic biology: cladistics (Parsons et al., 2003). Using this method, systemic biologists could analyze various shapes of bio-specimens quantitatively. Ordinarily, this computational approach has been used broadly in evolutionary biology.

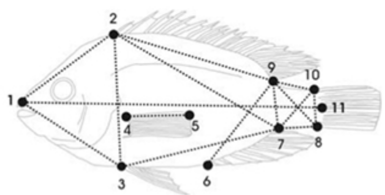
Morphometric methodology requires the identifiable morphological-factors that called 'landmarks'. The visible formal elements of fishes were used as landmarks in most researches those were conducted by morphometrics (Walker and Bell, 2000; Parsons et al., 2003; Zhang et al., 2009). And from the case of Kawakami's paper, we could get know that the bony elements also used to be good criteria to establish a group of landmarks (Kawakami and Yamamura, 2008).

In other words, a group of landmarks represent a morphological character of the one bio-specimen. And the quantification analysis is induced by visualization. Vector plots and thin-plate splines like geometrical visualization methods allow to generate visualization of 'differences', 'associations', 'variability', etc. (Slice, 2005).

Usually the physical representations of 1) length, 2) angle, and 3) area are quantified for a morphological analysis in morphometrics. As we mentioned in Fig. 3 the morphological factors – landmarks – define these physical representations. The adaptation of morphometric methodology on design analysis has been discussed positively in the analysis of artifacts (Cardillo, 2010). The changes of physical representations that are defined by landmarks are leading quantitative diagnosis. To adapt this methodology on a high-speed train design analysis the landmarks should be matched with the landmarks that are constructing an exterior shape of high-speed trains.

Adaptation of Morphometric Landmark Analysis

The idea of geometric classification to adapt morphometric methodology for analyzing train



	Morphological Factor	Details
1	1-11	The total length of the fish
2	2-3	The height of the fish
3	4-5	The length of the fin
4	9-7 and 10-8	The height of the tail
5	7-8-9-10	The area of the tail

Fig. 3. Truss Represented Fish Model (Parsons, K.J. et al. 2003)

front-head design variations was introduced in the dissertation of Kim that had a purpose which finding out a typical geometric structure of the front-head part in high-speed train design (Kim, 2008). He chose the 10 landmark features that represent a train front-head shape (Table 1). Generally these 10 landmarks are essentially representing a front-head part of high-speed train.

In this research, we detect the morphological differences of biomimetic-driven high-speed train front-head designs with others by morphometric analysis. Historically, Japanese high-speed train opened the new era of commercial high-speed transportation with the launching of the first high-speed train: *Shinkansen 0 Series* (1964). And an exterior shape of train front-head has been renovated from model to model. Sequentially developed models were designed by the research results of computational aerodynamic predictions, styling, manufacturing, and so forth. *0 Series*, *300 Series*, *400 Series*, *E1 Series*, *500 Series*, *700 Series*, and *N700 Series* were designed with the efforts toward overcoming the existing limits. And *500 Series* train was designed with biomimetic design concept. The biomimetic design concept was being used in a design process for the purpose of surmounting the engineering limits: aerodynamic drag, vibration, noise, etc. These serial front-head cases show the sequential changes of design.

The serial design cases – timely distributed *Shinkansen* high-speed train designs – can be good specimen in testing the influences of biomimetics and detecting these design evolutionary changes. By using the morphometric represented train bodies (Fig. 4) we analyzed the designs quantitatively. The design changes were detected by this morphometric analysis. The landmarks those are representing a characteristic of front-head shape were chosen through the researches that were conducted to establish the essential features.

	Morphological Landmarks	Landmark Label
1	Locomotive Connection Cab	LC
2	Lower Skirt	LS
3	Bogie Skirt	BS
4	Headlight	HL
5	Tail Identification Light	TL
6	Front Window for Driver's Cabin	FWC
7	Side Window for Driver's Cabin	SWC
8	Door for Driver's Cabin	DDC
9	Front Tip of Front-head	NT
10	Front-head End	NE

Table 1. Morphological Landmarks of Front-head Shape

Design Analysis for High-speed Trains

The morphometric analysis about front-head part of high-speed train is conducted with criteria such as 1) length, 2) leaning angle, and 3) area. To do this, first, the truss representation about front-head parts should be prepared. The length-directional maximum length of a front-head part defines the geometric factor of length (*NT-NE*). And the area, which is defined by morphological landmarks, describes the representative area of front-head. Lastly, the leaning of the representative linear that is calculated by the distributed landmark data represents the ratios and angles of the shape of train front-head. The each high-speed train design is quantified by these factors. Fig. 4 expresses the morphometric truss-structural view for each high-speed train profile.

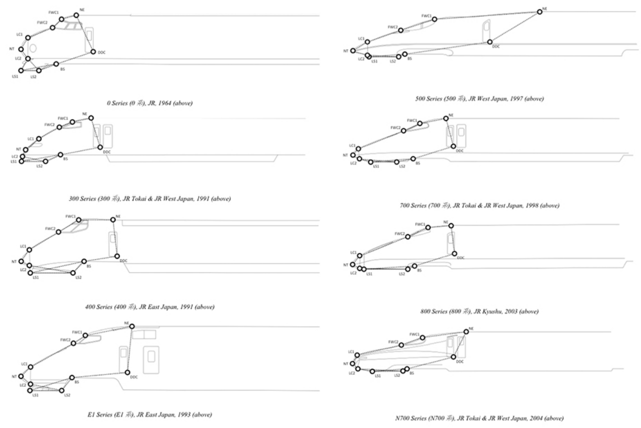


Fig. 4. Truss Represented Front-head Part of Train Designs (Refer Table 1)

Landmarks distribution of design cases is shown in Fig. 5. Most high-speed trains are analyzed above had 6~8 length of front-head. However, the case of biomimetic design-driven model – *500 Series* model – had 220% lengthened front-head. The leaning of each high-speed train design is calculated by using the landmark distribution that is structuring truss model (Fig. 4). The leaning of the representative linear that is calculated by the distributed landmark data, represents the ratios and angles of the shape of train front-head. The biomimetic-driven design model – *500 Series* model – has the lowest leaning value. Overall, the leaning value changes show the tendency that is converging on the value of *500 Series*. Andmost high-speed trains were analyzed above had 12~17 area of front-head part. Overall, the area-changing tendency shows the quite linear. However, noticeably, the biomimetic-driven design model – *500 Series* – has 172% extended side area.

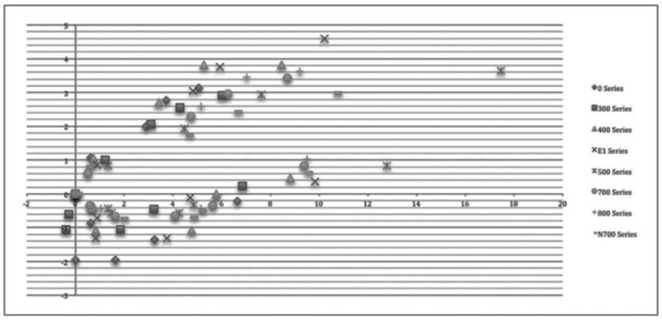


Fig. 5. Landmarks Distribution of Design Cases

Conclusions

In this research, we tried to diagnose practical limitations of current high-speed train design methodology and reveal the impacts of biomimetic approach in design point of view, with a case analysis about the Japanese high-speed train designs. In the timely distributed serial design cases, the *500 Series* of *Shinkansen* high-speed train was used as a representative example that was designed by biomimetic concept.

Ordinarily, engineering design process has been designed to guide designer's problem solving and design thinking. Basically, high-speed train design must satisfy the both design phases such as exterior shape development and aerodynamic prediction. However, the current high-speed train design methodology cannot enlarge the solution space that it can deliver. Even though, unfortunately, the current methodology supports predictability and robust model development, the methodology has limits because it cannot reflect of many other possibilities that would be generated by combining with other complex morphological shape features. The biomimetic design concept was introduced to complement this issue somehow.

The biomimetic design process of high-speed train is using bio-shape that is well qualified in aerodynamics. Thus, designers can develop the well-qualified design solutions and be possible to expect surmounting preexistence limits. The *Shinkansen 500 Series* shows how designers can enlarge the solution space that implies better aerodynamic performance by using biomimetic approach. And morphometric analysis results show the extremely different shape characteristics of biomimetic-driven design model. In the design process that is bridging gap between clear engineering-knowledge and vague design creativity, comparing the biomimetic approach with the current methodology, it can enlarge verity of solutions that designers can choose.

Until now, lots of high-speed vehicles were designed with the current design methodology. Nevertheless, the nature contains bunch of powerful solutions that we even did not concentrate before. The domain of biomimetic design has a bold interest at a life diversity collection. However, the absence of rigorous methodology in biomimetics still allocates it at experimental level. It is not doubtful whether the biomimetic design concept will break out stereotype of fixed streamlined solution or not. Yet, the biomimetics is not always a solution that broadens shape design possibility, if rigorous methodology is not supported.

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