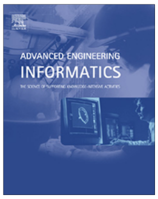
Advanced Engineering Informatics xxx (2014) xxx–xxx

Contents lists available at ScienceDirect

Advanced Engineering Informatics

journal homepage: www.elsevier.com/locate/aei



Parametric shape modification and application in a morphological biomimetic design

Sun-Joong Kim, Ji-Hyun Lee [*]

Graduate School of Culture Technology, KAIST, Daejeon 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 17 March 2014
Received in revised form 18 August 2014
Accepted 16 September 2014
Available online xxxx

Keywords:
Biomimetics
Parametric modeling
Shape modification
Morphometrics

ABSTRACT

Biomimetic design performed to develop a solution-shape has been offered as a successful approach for overcoming the limitations of typical design methods. Especially for the nose-shape of high-speed trains, the morphological characteristics of a superior bio-model were used in the design process. However, current design methods using the biomimetic approach, particularly in the morphological domain, do not support a technique to evaluate how close the new solution is to the optimal one; nor do they support alternative methodologies used to validate and verify the solution-shape being developed. Solution optimization in a biomimetic design means not only preserving the original shape of a bio-model but also validating and verifying it. Shape optimization for a design problem should accompany shape evaluation and modification conducted according to criteria involving both evolutionary traits and technological constraints. In this research we suggest a method to verify the original shape, and to validate the solution, using theoretical backgrounds from both systematic biology and evolutionary biology. In this paper, the morphological characteristics of a bio-model are verified and modified using a quantitative method. To validate the solution developed, new criteria are applied for high-speed-train design.

1. Introduction

Biomimetic design is an approach supporting development of design solutions by applying superior features or traits that exist in nature. Sources for these solutions may involve natural materials, mechanisms, morphologies or ecological characteristics [12,15,1,23,33,36]. Especially in cases of biomimetic design for vehicles, most designers use morphological models based upon the exterior shapes of fishes or birds, animals known to be aero- or hydro-dynamically superior species. Such shapes are also suitable for application to the basic shape of a vehicle. A basic shape provides the outlines of an exterior design of a vehicle before it is polished for mass production [1,19]. In fact, the conical nose shape of the Shinkansen 500 series high-speed train was proposed from a biomimetic design based on the bill shape of a kingfisher. The reason the shape was highly rated as a suitable (train) nose shape was the aerodynamic advantage gained when a kingfisher dives into the water to hunt a fish [26]. The bill shape of kingfisher is an adaptation to this ecological condition and the engineering designers reused that information to design a successful low-resistance shape for the locomotive nose [21]. As for other cases of biomimetic design, the morphological advantages of the bio-model were transferred to the basic shape of the vehicle by directly mimicking the original biological shape [15,21,26]. Before this, the morphological optimization of the train nose-shape was regarded as an extremely difficult problem because the mechanism producing energy loss—noise and vibration mostly produced by friction and vortices—is almost indefinable [30]. The biomimetic design that resulted in development of the solution-shape was considered a successful attempt to overcome the limitations of typical nose-design methods. However, even though there is no doubt that mimicking the original biological shapes will provide superior performance, optimizing a shape for a defined design problem means not only preserving the original shape of a bio-model but also “applying an analogy” [1,23,35]. The matter of shape optimization involves validation and verification of morphological features that are adaptations to achieve specific functions under particular ecological conditions [23]. This provides critical information to answer the question. “Is the developed solution-shape optimal for the design problem?”

In cladistics, shape of a bio-model is understood as an important trace of evolutionary adaptation of species to the conditions they encounter in nature [1,13,18,29]. Furthermore, each sub-feature consists of a shape that has also been adjusted by these conditional factors [13,29]. This explanation arises one important

---

[*] Corresponding author. Tel.: +82 42 350 3237; fax: +82 42 350 2910.
E-mail address: jihyunlee@kaist.ac.kr (J.-H. Lee).

http://dx.doi.org/10.1016/j.aei.2014.09.006
1474-0346/

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

message: morphological characteristics described in a bio-model have developed by a continuous process of evolution through the long-term adaptation of sub-features (e.g., eye-ridge, nose, or dorsal keel). One other important implication is that these long-term adaptations of sub-features are the results of a process for surmounting limitations imposed by environmental or ecological conditions [13].

A generalized analysis of how sub-features have evolved to achieve specific functional abilities is almost impossible; although, at least the performance of the inner mechanism of evolution, and functional explanations about why those sub-features had to be adjusted, are comparable and understandable from the perspective of synthetic evolution [12]. Using this academic agreement that sub-features have adapted in response to several functional requirements, cladistics researchers have defined categories and allocated species to form a phylogenetic tree. These functional requirements would be derived from environmental or ecological conditions [13,18, 29].

There are two reasons why these implications are important in this research. First, they provide a theoretical basis for the decomposition of a shape in a bio-model into sub-features for evaluation using a top-down approach. Second, they provide a theoretical background for the re-composition of modified sub-features into several solution-shapes using a bottom-up approach. Specifically, it is possible to evaluate shapes using a functional approach to shape decomposition, and by application of functional criteria originating from the problem definition. The criteria that originated from the problem definition (for example, the design criteria for the nose-shape of a high-speed train) are used in the evaluation phase to reflect the practical constraints of the design object. However, as we pointed out, previous cases in biomimetic design have not included verification and validation in the development of a solution-shape because previous efforts were too focused on mimicking the original shape and delivering its original characteristics. Thus, current practice in biomimetic design, especially in the morphological domain, does not support techniques by which to judge how close a proposed solution-shape is to an optimal solution; nor does it provide alternative methodologies to validate and verify the original shape to support the development of the solution-shape. It would be estimated that those involved in biomimetic design could not reuse information about long-term adjustment and optimization processes of a bio-model, but that has only increased the number of possible solutions available from searching an abundance of creative concepts from nature as the quantity of usable information has increased. However, validation and verification of the original shape characteristics can be achieved using evaluation of each sub-feature, and modification of each sub-feature, in relation to design constraints. The adaptation of parametric modeling from evolutionary biology using interdisciplinary knowledge, could provide a complementary methodology by which to validate and verify the original bio-model shape, allowing designers to seek a solution-shape closer to optimal for each specific design challenge.

In this research, we developed methods for parametric shape modification, and their application to accomplish the validation and verification for the original bio-model shape of interest. In particular, as a case study, the nose shape of a high-speed train was designed using the proposed biomimetic design methods; Boxfish is used for this study. The methodology for decomposing the original shape of a bio-model was developed from evolutionary knowledge provided by biological studies. To figure out the design criteria of the product, the nose shapes of high-speed trains were traced using a quantitative method. The design criteria revealed were then used for shape modification and application. Each modified sub-feature of the bio-model was provided in the form of a number of alternative solution-shapes, and these were evaluated by simulation. This methodology would be a good step toward the development of a practical process for robust shape modification, and would provide a complementary method by which to address the current limitations of morphological biomimetic design.

2. Related work

2.1. Biomimetic design

Biomimetic design is an alternative approach by which to apply a superior form or mechanism that exists in the nature, to solve a particular problem [15,23,36]. Typically, the function desired of a design project is the key to evaluating the effectiveness for the defined problem, of the form or mechanism of the bio-model chosen [15,23]. However, there is a "large" and "obvious" gap between choosing a bio-model and making it effective, that has highlighted the need for a new methodology to relate these in a systematic way [15]. The gap is still the main obstacle in systematic-design modeling methodology, even though early biomimetic design dates back thousands of years [15]. The close relation of the biological knowledge of a designer and the potential for solving a specific problem in biomimetic design is also not absolutely irrelevant [15,23,36]. Motivation to use even this currently-limited design approach is still valid because the high probability of providing a superior solution to the market is supported by previous cases [33]. The fact that there exists limited methodological support for this design approach is not negligible, but at least quantitative and qualitative enhancements have been made, from the perspective of attaining a solution set [5,23].

In several pioneer studies focused on the design of cruising vehicles (e.g., automobiles, trains, and submarines) researchers aimed to adapt typical cruising shapes from appropriate bio-models to provide their basic shapes [6,9,25,31,38]. Ecological knowledge as a complement to engineering design is believed to provide a way to increase the probability of developing ideas for superior engineering solutions [14,17,33]. When used to provide the basic exterior shape of a vehicle, simple parameterized bio-shapes have been helpful in designing low-resistance vehicle models. However, even though ecological knowledge may be applied to parametric shape-modification, the defining issue of morphological parameters remains: specifically, morphological parameterization and its analysis.

Kindlein and Guanabara summarized [23] the neutral process that engineers face when they solve a problem using a bionic (bio-inspired design) approach. In this research, the overall process of biomimetic design was decomposed to (1) sample selection, (2) sample collection, (3) sample preparation, (4) sample observation, (5) parameterization, (6) creating analogy between the natural system and the product, and (7) application of biomimetic design to the project [23]. These sequential design stages roughly point out how designers can introduce biological knowledge into the general design process. However, even though sequential models were established, the research was restricted to domains of natural science. Conclusively, the highly problem-oriented character of biomimetic design did not encourage the appearance of a universal design methodology [33].

2.2. Top-down and bottom-up approaches for shape analysis and modification

In biomimetic design, a design approach has been developed by which to apply biological knowledge to the design process. Biomimetic-driven, problem-solving design requires the use of a bio-model. Inadequate biological or ecological knowledge in a

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

biomimetic design occasionally causes suitability issues regarding the engineering solution being developed. The roles of top-down-based understanding of the bio-model, and bottom-up-based solution development in general biomimetic design, were diagrammed below (Fig. 2.1).

Usually, the top-down approach is generally applicable for understanding bio-models. In particular, to understand the aerodynamic properties and morphological characteristics of a bio-model, the model should be finitely decomposed to the appropriate level. Unfortunately, top-down biomimetic analyses do not provide clear criteria for understanding parametric model decomposition. This is because most biomimetic designs are conducted at nano or micro scales, rather than at macro scale. Although existing cases of biomimetic design cannot support the criteria for parameterization, the morphometric approach, which has been used to support bio-model quantification, provides methodological criteria that may be used to decompose one bio-model into several parameters defined at a meaningful level. In addition to its application to design problems in hydrodynamics and aerodynamics, the top-down approach also reveals bionic properties that could not have been introduced before [1].

However, at the stage of generating solutions (i.e., developing an engineering solution for the problem faced) the top-down approach cannot support the application of pertinent biological knowledge [1]. To apply the original bio-model to the engineering solution, and to include biological knowledge, a bottom-up approach is required: the principle-applied composition of possible design alternatives supports the appropriate derived-solution, via evaluation for alternatives. The bottom-up approach of biomimetic design has advantages in the application of sub-solutions, and the generation of alternatives. The predefined criteria of model-modification, guide the morphological deformation used to generate sub-solutions that serve as sub-features for a design alternative that will be composed of the new sub-features generated. This process is controlled robustly by the defined criteria. Designers can expect robustness at the design phase by using the bottom-up approach. The sub-features making up the alternative models are evaluated by engineering criteria to derive appropriate solutions. The sub-features generated provide varieties of alternative design. This process can allow multivariate consideration during the phase for generating design alternatives [1].

2.3. Landmark-based shape decomposition and parameterization

To reveal the functional potential of a shape in a biomimetic design, understanding the compositional result added by the function of each sub-feature is as important as understanding the biological mechanism that developed each specific sub-feature of a shape. In particular, the application of a morphologically superior bio-model to a design project, introduces a fundamental objectivity in achieving an optimized manifestation of the desired function. This is the reason why post-manipulation of the morphological features defined by the chosen bio-model must be conducted using engineering criteria defined by a problem, including a sense of validation and verification. This is the point of the bottom-up approach upon which this research is focused. Technologically, the bottom-up processes for composition and reevaluation have been methodologically reviewed, and used in many nano-scale biomimetic design studies; even the concept has been theoretically discussed in the field of bioinformatics. However, a systematic method for defining the sub-features of a bio-model, have not been proposed for macro-scale biomimetic design. For these reasons, there is a clear need to develop a method supporting a top-down approach for shape decomposition and evaluation; specifically, the method has to be applicable for decomposing complex and atypical shapes.

Some time ago, evolutionary biologists needed a method that would allow comparison of morphological differences observed, and that could provide evidence to judge trends in the evolutionary flow [16,27,32]. With the (then) newly developed method, biologists were able to compare specimens and thereby judge their hierarchical positions in the flow of evolution. This quantitative method, morphometrics, was developed to evaluate and quantify the complex atypical shapes of bio-models [16]. Accordingly,

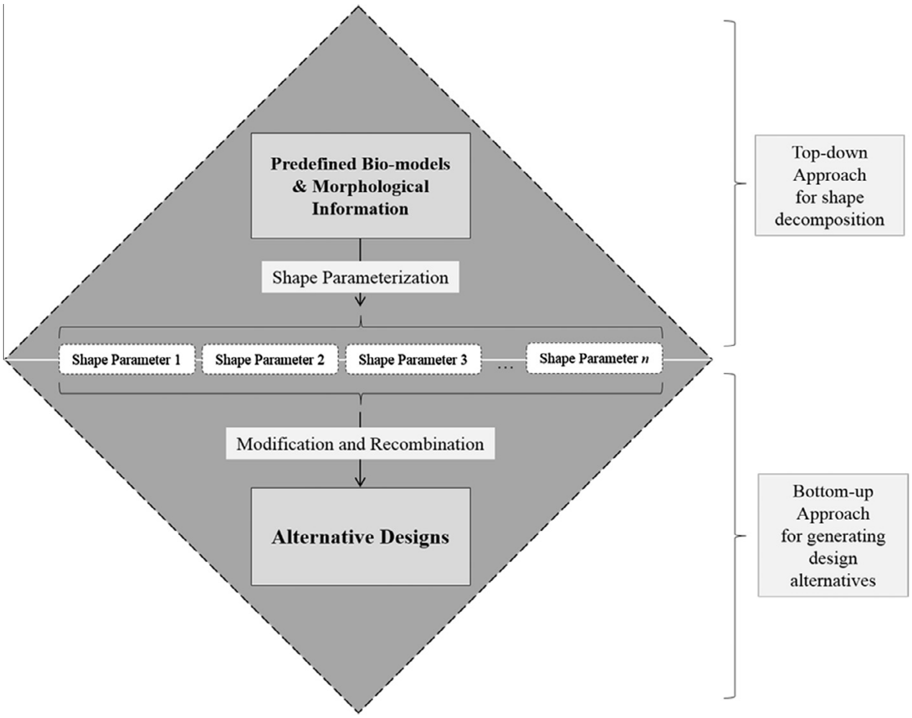


Fig. 2.1. Top-down and bottom-up approaches in the biomimetic design process.

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

morphometrics provides the theoretical foundation for shape decomposition required for the top-down approach to define the sub-features that make up a complex shape. This method is also used to trace the process of change appearing in a time-series of excavated artifacts because the method is applicable for analysis of objects which have complex and atypical shapes. This could be understood as an attempt to reveal the 'evolutionary' characteristics implied in the morphological changes of artifacts [8,10,39].

Most research focused on morphometric analysis of a form has occurred in the field of evolutionary biology. Biologists have used this quantitative method to trace species and to position a specimen on the tree of phylogenetic classification. For example, the formal sub-features of fishes were defined as landmarks [41] and the traces and quantifications of those landmarks revealed trends in the morphological deformation of species [11,28,37,40,41]. In addition to defining such landmarks using the exterior features of specimens, biologists also use interior, bony elements to trace evolutionary changes [20,24].

3. Methodology

3.1. Design method

According to the design research of Kindlein and Guanabara [23], the biomimetic design process consists of five steps: (1) search for a bio-model appropriate for the defined design problem, (2) verification of the morphological feature of the chosen bio-model, (3) adaptation of biological parameters, (4) evaluation of the morphological feature using problem-oriented criteria, and (5) implementation of a shape for manufacture. The biomimetic process used to create a nose design for a high-speed train, the stated overall goal of this study, also basically follows these steps (Fig. 3.1).

The morphological parameters chosen should be applicable for the generation of design alternatives. The practical definition of parameters for the basic shape represented by the bio-model is conducted using morphometric methodology. This is essential to bridge the gap between design quantification and biological knowledge. The systematic and quantitative methodology provided by morphometrics, born in evolutionary biology, has itself been adapted for the quantitative analysis of bio-shapes. By developing this systematic framework, engineering designers were able to adapt a computational tool for quantitative bio-shape analysis [10,28]. The morphological parameters defined by morphometrics can support the appropriateness of shape modifications.

Second, definition of the criteria applied to shape modification is related to the engineering problem. The shape of the chosen bio-model has to be modified using problem-oriented criteria before adapting it to provide a solution [1,23]. The issue of robustness in biomimetic shape modification has been supported by the bottom-up design approach used in most nano-scale design research [22,34]. The bottom-up-based parametric modification of the original bio-shape can provide robustness with regard to the chosen parameters, and to the criteria of modification.

In its first step, this work involved pioneering research on a Boxfish-shape-adapted high-speed train model (hereafter referred to as BTM). (The term boxfish is applied to a group of more than 20 species in Family Ostraciidae.) The aerodynamic effect from use of the BTM provided outstanding simulation results. This BTM is based on one of the lowest-resistance shapes in nature [2,3,6] , and the superior results from simulations by these workers, was regarded as due to the morphological advantages of the Boxfish shape. The Boxfish shape adapted to the high-speed train model here also provided superior simulation results, but the specific causal relationship was not revealed in these results. Even though the interrelationships by which each morphological feature impacts the overall aerodynamic property was not revealed experimentally, all such findings support the theoretical reasons for applying the Boxfish bio-model to the shape-optimization of the front part of a high-speed train.

Typically, the biomimetic concept implies that the design work include analytical verification of the bio-model according to criteria specified by the design-problem. However, the approach to model verification has not yet been developed in a systematic way. Although biomimetic studies could not provide support for a systematic theoretical concept, in this research, a systematic framework was adopted (and adapted) from biological studies. In the domain of high-speed-vehicle design, for trains in particular, the open-country running condition is given priority [19]. This cruising condition was recognized as one of the most important factors for determining the efficiency of trains, during verification research intended to interpret the aerodynamic characteristics of fish-like shapes (which, after all, are adaptations for movement through water, not air). These scientific approaches allowed the adaptation of these systematic frameworks, and of the defined morphological features (landmarks), for biomimetic design work.

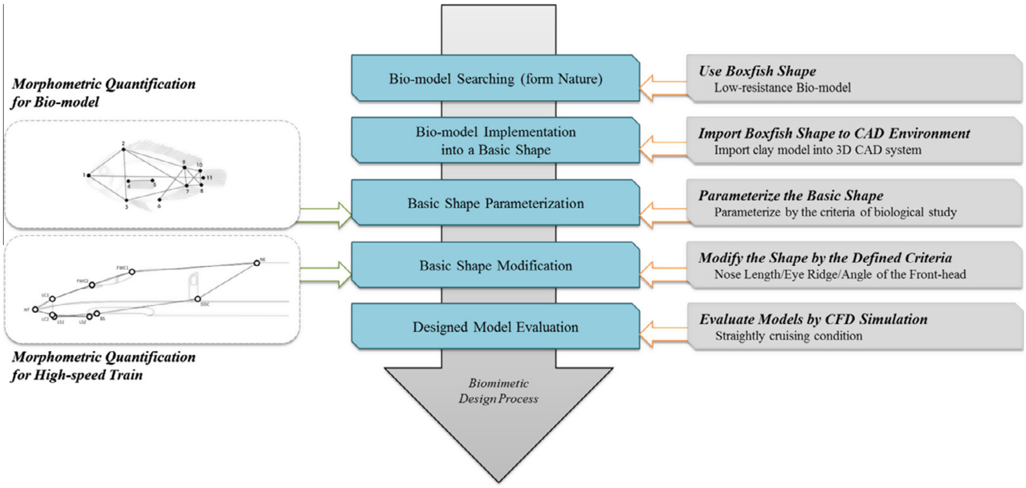


Fig. 3.1. The biomimetic design process of this research.

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

Third, the morphological features described by the bio-model should provide criteria by which to commence modifying the original shape to a shape optimal for the nose of a high-speed train (the defined design problem). In other words, the quantitatively explained aerodynamic adequacy of the modification has to be constructed out of morphological features predefined by bioengineers. As for the definition of the morphological parameters, connecting the result of morphologically-analyzed high-speed train design and the result of the morphologically-analyzed bio-model (Boxfish) supports the adequacy of the defined morphological features (parameters) as to whether these parameters have appropriate meaning for this specific problem [7,10].

Fourth, the developed vehicle models should be evaluated by criteria revealed in the problem domain. In this research, Computational Fluid Dynamics (CFD) simulation was used to evaluate the aerodynamic characteristics of the newly designed vehicle model. As mentioned above, high-speed train vehicles are usually tested under the assumption that the designed train model is running on a straight railroad constructed in the open [19]. (Velocity: 88.333 m/s, Gap between train and rail: 300 mm, Density of air: 1.225 kg/m^3, Temperature of air: 288.16 K, Viscosity of air: 1.789e-05 kg/m-s, Ratio of specific heats: 1.4.)

3.2. Parameterization and shape modification

In this research, biological knowledge was introduced into the biomimetic design-process using the bottom-up approach. This approach has been widely used in nano-scale biomimetic design due to its advantages for morphological manipulation. The imported, 3D-shape information of the bio-model has the format of points cloud. Each point in the cloud contains specific location information. In this sense, the points cloud model represents the entire bio-model after scanning with a scanning tool; finely scanned points should be relocated using Cartesian coordinates. Parameterization of the bio-model implies the classification of points. The tendencies of the line segments linking two neighboring points were used as criteria for point- classification. The definition of each morphological parameter, based on morphometric knowledge, was matched with classified points. This required the modification of each morphological parameter used in the BTM, according to the criteria predefined from the landmark analysis (Fig. 3.2).

Defined modification-rules numerically guide the modification of a basic shape by each morphological parameter. Thus each parameter is modified according to the shape-modification criteria. Especially in this research, the nose length, eye-ridge, pitch angle, and the side area of the BTM head were modified by the defined criteria. Morphometrically analyzed train designs provided quantified data for the total exterior length of the nose (*NS-CV*), the height of the nose (*CV-LS*), the slope of the representative line (linear representation of distributed landmarks), and the area of the side of the nose (area of the overall truss structure) (Fig. 3.3). Each set of quantified data was applied to achieve the shape modification.

Existing high-speed trains have nose structures about 6–8 m long, but the BTM model had a nose length of about 4.2 m, set by the original proportion of Boxfish bio-model. Although, it showed superior aerodynamic characteristics in this form, this model should also be used to predict results for nose- structures of other lengths. With this in mind, the research simulated models with alternative nose-structure lengths. Thus, to detect the effects on aerodynamic characteristics when the nose length is changed, the researchers controlled the points representing the nose parameter, to proportionally extend the length-directional components by 0.125 times.

The aerodynamic effect of the eye-ridge has not yet been detected. When applying the bio-model in high-speed trains this eye-ridge feature can give either a beneficial or detrimental aerodynamic effect. To predict the aerodynamic tendency resulting from the eye-ridge parameter, this research should consider this parameter an independent variable. To detect the effects of eye-ridge-removal on aerodynamic characteristics, researchers controlled the points representing the eye-ridge parameter to create two options (eye-ridge present and eye-ridge removed). When the eye-ridge was removed, researchers controlled the points of the extended splines.

The pitch angle of exterior model was one of the major parameters used for the aerodynamic bio-model experiment. This experiment was adapted from the Boxfish exterior model research of Bartol et al. [4]. Along with the lines, in the existing high-speed train designs, the slope-angle of the front of the head-structure should be modified and evaluated during the design process. Actually, the angle factor was not considered in traditional vehicle design processes; however, the design process inspired by inclusion of ecological information made it prudent to verify bio-mimic models using biological aerodynamic or hydrodynamic properties from biological studies.

The area of the exterior model was widely used in the morphometric analysis. The calculated area of the truss-expressed shape represented the character of the shape. However, like the pitch angle factor, the area factor needed to be verified before introducing the factor into one of the modification parameters because the factor had not yet been verified as an aspect of train-design.

4. Result

4.1. Landmark analysis for shape modification

4.1.1. Quantified Result 1 — Length of the train nose-structure

Most of the high-speed trains analyzed had nose-structures from 6 to 8 m long. Overall, the graph in Fig. 4.1 shows the tendency toward increase of the total nose length, model by model. This implies a need for nose-length transformation and related shape modification. For the nose-length transformation, this research used a transformation of the length-directional nose-part from 6 to 8 m.

4.1.2. Quantified Result 2 — Slope of the train nose

The nose-slope of each high-speed train specimen was calculated using the morphometric truss model (used for shape quantification, see Fig. 4.2). The slope represents the ratios and angles of the shape of the train nose. The graph shows quite unsteady tendencies in the slope changes (Fig. 4.3). This implies the need for nose-angle transformation and related shape modification. The nose transformation criterion in this research was the angular transformation from 0.2 to 0.35.

4.1.3. Quantified Result 3 — Area of the train nose-structure

Most of the high-speed trains analyzed had a nose area of 12–17 m. The graph in Fig. 4.4 shows the quite linear tendency of area, model by model. The tendency is one of gradual increase, but this tendency should be understood in relation to variations in the nose length. The nose area showed a tendency toward gradual change in relation to changes in the total nose length because the height of the high-speed trains was quite uniform. This makes it hard to consider the area factor as a modification parameter. In order to consider only the independent factors in morphological modification, the area factor was not considered a modification parameter in this research.

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

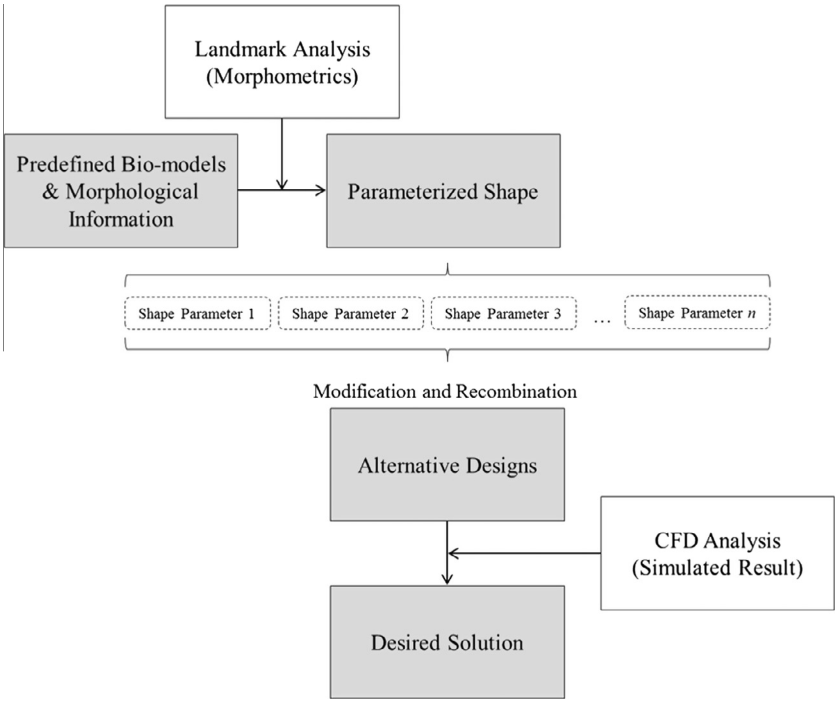


Fig. 3.2. Framework for shape parameterization and modification.

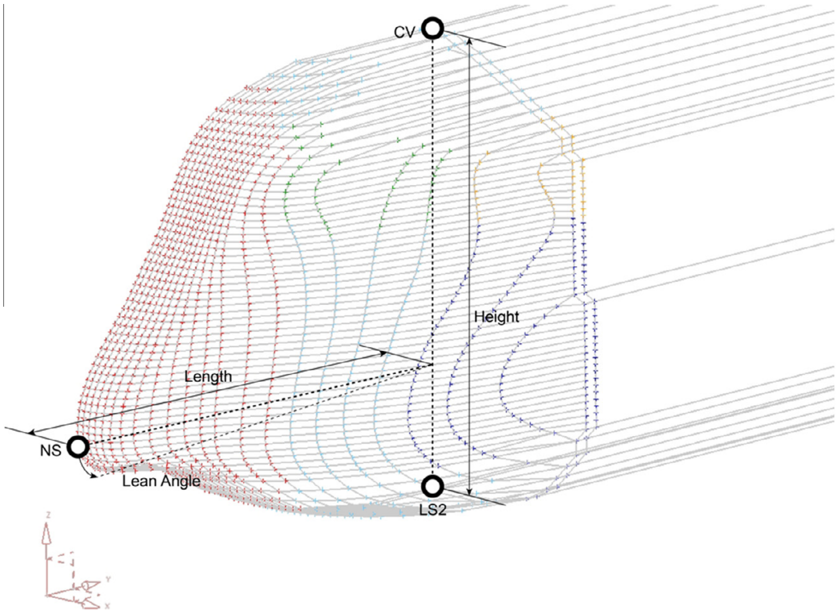


Fig. 3.3. Parameter definition of BTM.

4.2. Parametric model generation

4.2.1. Parameter 1 — Length of the train nose

In this research, the bio-mimic train model (BTM) has the shape of the Boxfish bio-model; the size was rescaled to the real size of a high-speed train but the proportion of each feature was not changed.

Existing high-speed trains have noses about 6–8 m long, but the BTM nose was about 4.2 m long (the original proportion of the Boxfish bio-model). Although, the nose at this size showed superior aerodynamic characteristics, this model should also be used to predict such characteristics when the nose length is transformed. To indicate the tendency when the nose length is transformed, models were used to simulate conditions when the nose length was varied. Thus, to detect the effects on the aerodynamic characteristics when the nose length changed, the researchers controlled the points representing the nose parameter to proportionally extend the length-directional components by 0.125 times (Table 4.1).

4.2.2. Parameter 2 — Eye-ridge of the train nose

The aerodynamic effect of the eye-ridge has not yet been detected. When applying the bio-model in high-speed trains this eye-ridge feature may give either beneficial or detrimental aerodynamic effect.

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

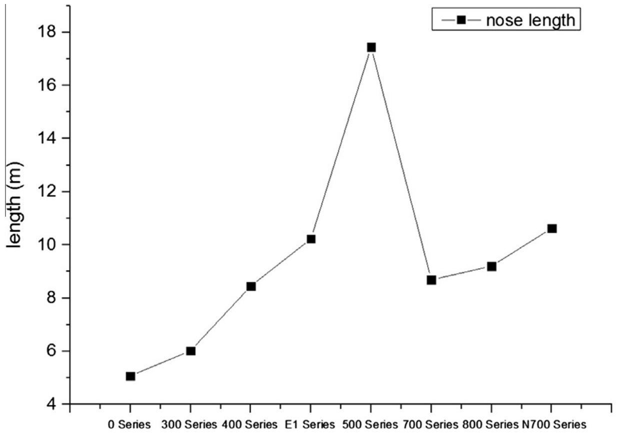


Fig. 4.1. Nose length variations of high-speed train specimens (plotted by Origin).

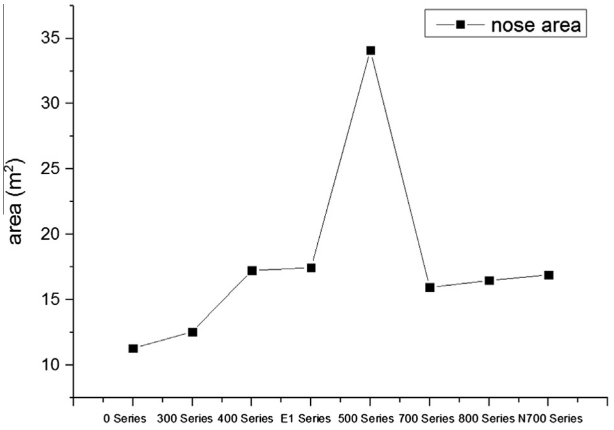


Fig. 4.4. Variations in nose area of high-speed train specimens (plotted by Origin).

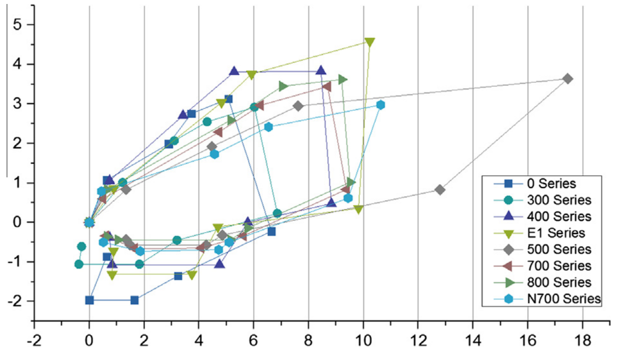


Fig. 4.2. Linearly-represented nose of each high-speed train design (plotted by Origin).

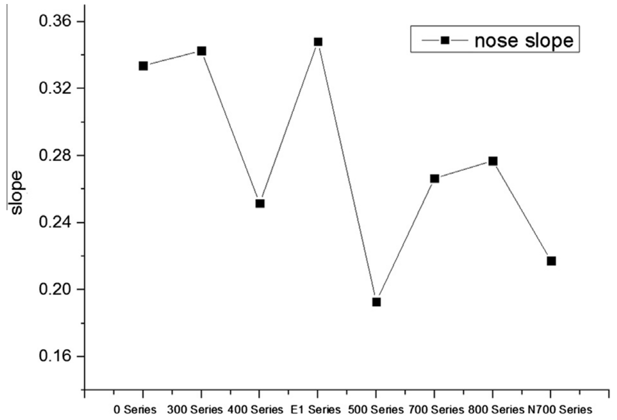


Fig. 4.3. Variations and tendency of the slope of the nose (plotted by Origin).

To predict the aerodynamic tendency observed for the eye-ridge parameter this parameter should be considered an independent variable. To detect the effects on aerodynamic characteristics when the eye-ridge is removed, the researchers controlled the points representing the eye-ridge parameter to provide two options (eye-ridge present and eye-ridge removed). When the eye ridge was removed the researchers controlled the points of the extended splines (Table 4.2).

4.2.3. Parameter 3 — Angle of the train nose

The slope angle of the exterior model, was one of the major parameters of the aerodynamic bio-model experiment. This experiment was adapted from the Boxfish exterior-model research of Bartol et al. [4]. Along with the lines, in existing high-speed train designs, the nose-slope angle of whole front of the nose-structure should be modified and evaluated during the design process. This angle factor was not considered in traditional vehicle-design processes but the design process inspired by the inclusion of ecological information called for the verification of biological aerodynamic (or hydrodynamic) properties from biological studies.

From the morphometric analysis conducted during analysis of existing high-speed trains, the criterion of the angular transformation was defined. In this research, the nose transformation criterion was angular transformation from 0.2 to 0.35. Thus, to detect the effects on aerodynamic characteristics when the nose angle changed, the researchers controlled the points representing the nose angle parameter to steadily tilt the components in 0.05 degree intervals.

4.3. Generated model evaluation

4.3.1. Parameter 1 — Length of the train nose

This research used a CFD simulation to identify the relationship between nose length and aerodynamic characteristics.

As a result of the simulations, a tendency was found toward a decrease in the total coefficient as the nose length increased. However, to identify the total tendency, designers should analyze each tendency of the pressure coefficient and the viscous coefficient separately. The total coefficient is represented by the sum of the pressure coefficient and the viscous coefficient.

Regarding the pressure coefficient, the value decreased with increasing nose length. However, in regards to the viscous coefficient, no steady tendency was detected.

The tendency of the pressure coefficient is shown in Fig. 4.5: the pressure coefficient decreased when the nose length increased. The viscous coefficient also generally decreased (Fig. 4.6), but at particular points the values showed an irregular tendency.

As can be seen in Fig. 4.7, the plotted graph of the pressure coefficient and of the total coefficient are very much alike. Concisely in this case, the total coefficient, numerically representing the aerodynamic drag, is obviously dependent on the value of the pressure coefficient, not on that of the viscous coefficient.

This interesting correlation result should be understood in relation to aerodynamics. As the length of the train nose increases, the total coefficient of the vehicle decreases. When this happens, the tendency is almost linear. This means that considering only the nose length does little to confirm whether the model is proper. The model should be considered from the aspects of material and of statics. This result suggests a guideline for developing an

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

Table 4.1
A summary of the nose length modification.

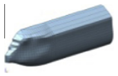
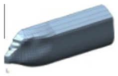
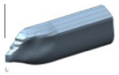
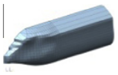
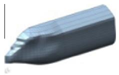
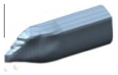
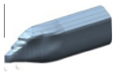
Nose 1.000	Nose 1.125	Nose 1.250	Nose 1.375	Nose 1.500	Nose 1.625	Nose 1.750
						

Table 4.2
A summary of the eye-ridge parameter modification.

	Nose 1.000	Nose 1.125	Nose 1.250	Nose 1.375	Nose 1.500	Nose 1.625	Nose 1.750
Eye Ridge	Y N	Y N	Y N	Y N	Y N	Y N	Y N

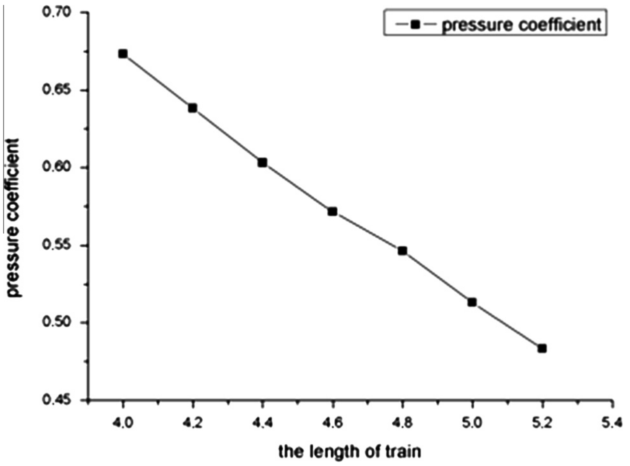


Fig. 4.5. Changes in the pressure coefficient (plotted by Origin).

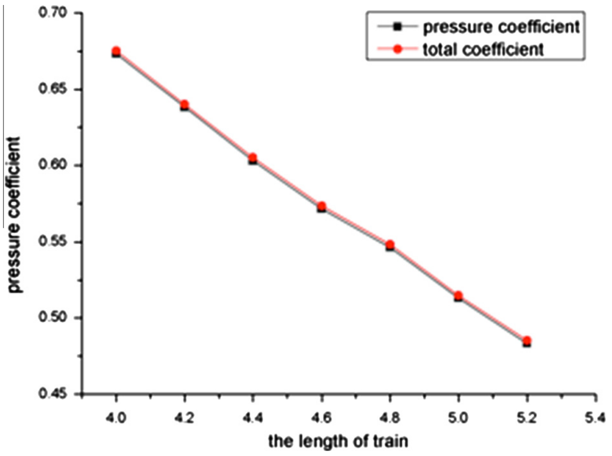


Fig. 4.7. Tendency of the pressure coefficient and of the total coefficient.

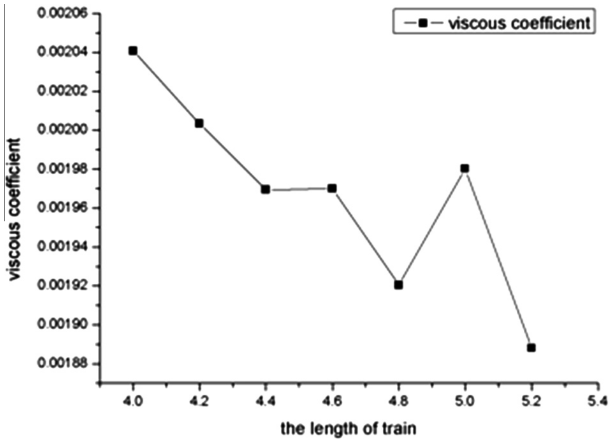


Fig. 4.6. Changes in the viscous coefficient (plotted by Origin).

optimal high-speed train model. When developing an optimal high-speed train design, designers should consider all the different available features together, and not only design a streamlined nose. This result also implies the necessity for development using a complex-shape model that could combine other morphological features with the streamlined nose shape. In other words, it implies the limits of the existing high-speed-train design process.

4.3.2. Parameter 2 — Eye-ridge of the train nose

Identification of the effects of the eye-ridge was focused on detecting its aerodynamic influence when it was applied to a high-speed train. Biological study of the bio-model suggested that the eye-ridge be chosen as a parameter to identify its role. Of course, such a ridge has several genetic possibilities, but in this step this research was focused on two representative options. One is that it is intergraded in self-optimized progress to adjust under the environment positively and the other is that it is inserted inevitably in intergraded progress for the necessity to get eyes negatively. To identify the effects from this parameter, a comparison simulation was constructed using CFD analysis.

The total coefficient values, and the pressure coefficient values, have differences but their trends are similar (Fig. 4.9 and Fig. 4.10). Actually in Fig. 4.8 the viscous coefficient has a smaller variance than that of 'eye-ridge present'. In summary, the existence of the eye-ridge has no practical impact on the total coefficient.

As a result of this simulation, the eye-ridge feature was underlying in a correlation with fluid-dynamic characteristics of a bio-model. However, it is clear that the eye-ridge feature does not provide beneficial effects in the high-speed-train model. Including the eye-ridge in the biomimetic design will only increase uncertainty in the design process, and will not provide aerodynamic benefits. This conclusion is supported by the fact that the result was similar when the eye-ridge was removed (in the simulation). This also means that, when the eye-ridge feature has been removed, the developed model will be more predictable in terms of its aerodynamic characteristics. Thus, from the predictability point of view, the eye-ridge feature should be removed when the Boxfish bio-model is applied to high-speed trains.

4.3.3. Parameter 3 — Angle of the train nose

Identification of the effects of angular transformation was focused on detecting the aerodynamic effect of changing the slope

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

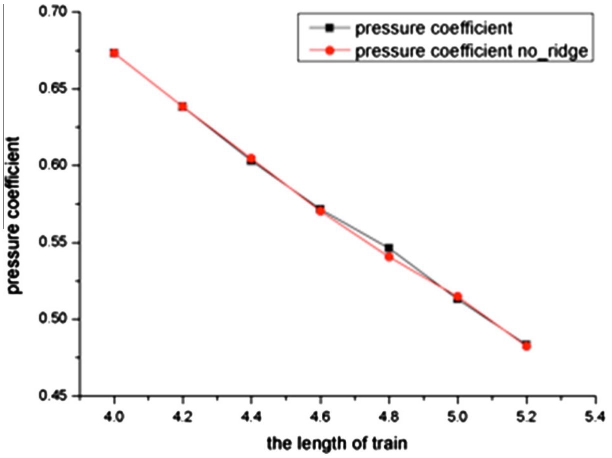


Fig. 4.8. The changes of the coefficient values when the eye-ridge feature exist or non-exist (*X* axis; the changes of nose length). Changes in the pressure coefficient caused by the eye-ridge.

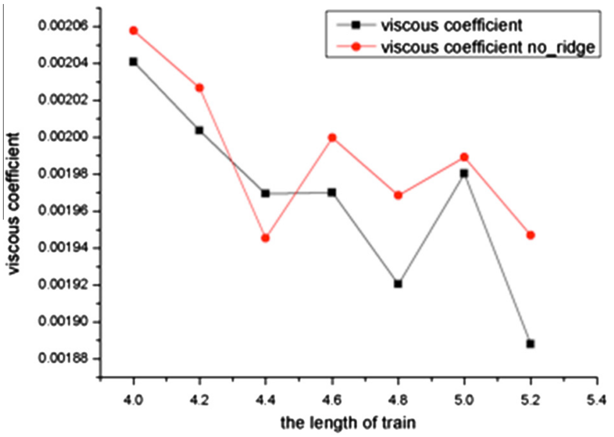


Fig. 4.9. The changes of the coefficient values when the eye-ridge feature exist or non-exist (*X* axis; the changes of nose length). Changes in the viscous coefficient caused by the eye-ridge.

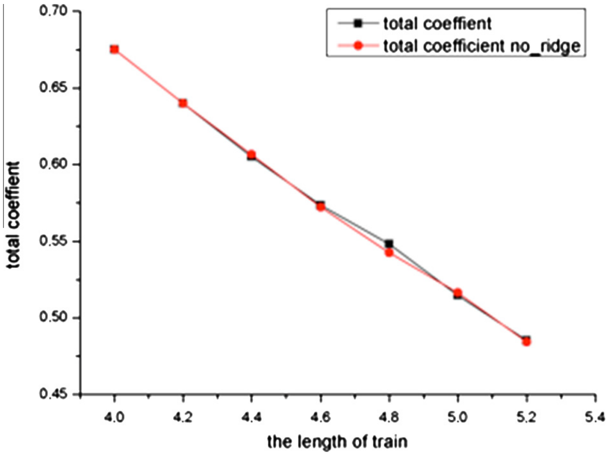


Fig. 4.10. The changes of the coefficient values when the eye-ridge feature exist or non-exist (*X* axis; the changes of nose length). Changes in the total coefficient caused by the eye-ridge.

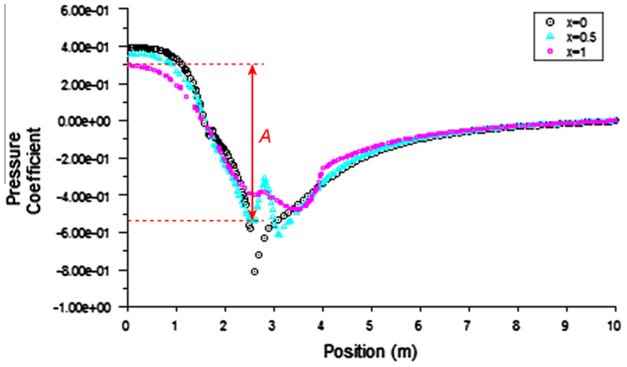


Fig. 4.11. The pressure coefficient values follow the train surface of length-direction. Train nose model with slope 0.35.

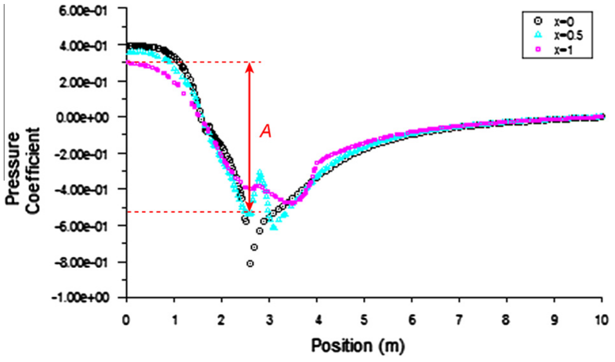


Fig. 4.12. The pressure coefficient values follow the train surface of length-direction. Train nose model with slope 0.30.

of the nose. After morphometric analysis of existing high-speed trains, the pitch angle was chosen as a parameter to verify its effects. Following the defined criteria, the researchers simulated the aerodynamic characteristics of the nose with three slopes via angular transformation (0.35°, 0.25°, and 0.05°).

As represented in Figs. 4.11–4.13, the decreasing variance between the maximum values with minimum value (**A**) became smaller as the nose angle decreased.

4.4. Discussion

In this research, evolutionary knowledge was used to verify and validate the shapes used to design the nose-structure of a high-speed train. The knowledge occurred in the form of the methodology of morphological analysis, which is used to quantitatively evaluate atypical shapes of specimens. In evolutionary biology, this method is widely used to compare morphological traits. As we have explained, the morphological output that designers use in biomimetic design is the synthetic output based upon the adaptations of each sub-feature. That is why the morphological or functional traits of each sub-feature are being quantitatively compared to trace the process of evolution. This provides a basis for our methodology, which takes a parametric approach based on morphometrics. Thus, the verification and validation of a shape is conducted by evaluation of each of its sub-features. Simulation was used to evaluate the synthetic result of modified sub-features.

By evaluation of the model, this study derived the tendencies in the aerodynamic characteristics when the nose length, eye-ridge, and nose slope angle were transformed by the selected criteria. In the simulation involving nose length, when the nose length of the basic shape increased the aerodynamic drag was reduced. Interestingly, this was found to be a direct linear relationship. When the nose length was extended in the modified bio-model,

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006

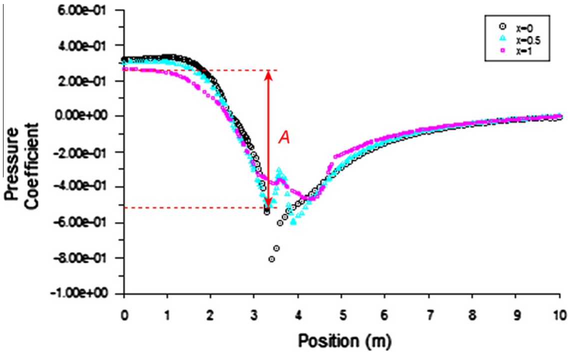


Fig. 4.13. The pressure coefficient values follow the train surface of length-direction. Train nose model with slope 0.25.

the result was less aerodynamic drag; a tendency also found in other studies involving smooth nose shapes. This tendency implies that when applying the Boxfish bio-model to high-speed trains, the designer has to consider interactions caused by other features of complex shapes. Thus, before biomimetic design is conducted the correlation between component morphological features should be identified.

Relatively, even removing the Boxfish eye-ridge showed a noticeable result. Interestingly, when the eye-ridge was removed, there was a tendency for the aerodynamic drag to show a steady rate of change. As has been shown, in high-speed train design, predictability is of critical importance. In contrast to when the eye-ridge was present, removal of the eye-ridge resulted in steady change and reduced aerodynamic drag, making it more appropriate to leave this feature out of high-speed train designs. Following these simulation results, it was concluded that the eye-ridge feature was purely related to the eye and should not be incorporated in high-speed train designs.

Last, decreasing the slope angle of the front (nose) of the train induced decreases of variance between the maximum pressure and minimum pressure. The steep variance between maximum pressure and minimum pressure causes inappropriate vortices when a high-speed train is cruising. If the nose-slope angle of high-speed trains was changed to 0.25 (the mean value of existing high-speed trains), design engineers could expect less of the vortices and resistance caused by the pressure variance at the front. Following these simulation results, it was concluded that the slope angle of the front should be adjusted using the chosen criteria.

In summary, the modified model (BTM) had aerodynamic advantages compared with the basic shape of the Boxfish bio-model. From the perspective of total coefficient, the BTM (nose length: 8 m, eye-ridge removed, slope: 0.2) provided a 21% reduction of the total drag coefficient. Usually the total coefficient value is used to evaluate the aerodynamic character of designed object. The result of the CFD analysis indicated conditions during the cruising condition of a high-speed train. The aerodynamic characteristics indicated by this analysis can be considered with other research that was conducted to define the other driving conditions of a high-speed train.

5. Conclusions

The efforts for biomimetic design have been focused on delivering morphological advantages, by direct mimicry of the chosen bio-model shape, to a design object. However existing design cases based on the biomimetic approach imply that direct mimicry is not the best way to achieve an optimal solution. In this research, the weaknesses in verification and validation of the chosen shape are specified. Unless these weaknesses are surmounted, the concept of optimal design using the biomimetic approach is inexplicit. Computational methods might provide a solution for the issues of shape verification and validation. Specifically, application of parametric shape modification is proposed to accomplish the research goal. From the methodological point of view, the biomimetic-design approach is noteworthy because it guides designers to solve a design problem by applying evolutionary procedures (adaptation) or by including evolutionary input during the design process as design knowledge. Thus the systematic methods (parametric shape modification and application) should be informed by evolutionary knowledge. More specifically, the shape parameters that we defined should provide the evolutionary background of a species. The methodology of morphometrics was created to quantitatively compare the morphological traits diversified through evolutionary processes. This methodology is applicable for the quantitative comparison of shapes, especially for comparison of atypical shapes, because most of the morphological traits of species are atypical. In this research, the shape parameters defined using morphometrics were used for shape modification and application. In addition to the use of morphometric methodology, was the use of landmarks to parameterize the bio-model. Using a Boxfish bio-model, known to be a low-resistance shape, the front (nose) of a high-speed train was designed. The applied landmarks (parameters) were drawn from the background research conducted to examine the aerodynamic properties of these Boxfish shapes: nose, eye-ridge, and hydrodynamic pitch angle. Even though this design case could not deal with other bio-models, the landmark adaptation process addresses the need for a methodology to parameterize models.

The criteria for shape modification were adapted from the analyzed results of high-speed-train fronts designed by Japanese railway companies. To analyze existing high-speed train shapes, morphometric methodology was applied in this design process. The landmarks needed for shape analysis were adapted from the design study of high-speed trains, and fundamental design elements for train nose design were adapted. By using morphometric analysis the most important criteria for shape modification were found to be the length, area, and nose-slope angle. Using bottom-up model generation, several alternative designs were generated. The defined criteria guided the modification of the basic Boxfish bio-model. Analyzed results from the morphometric design analysis suggested that the research should include length-directional nose transformation, two eye-ridge parameters (presence and absence), and nose-slope angle transformation. CFD simulations were conducted to evaluate the aerodynamic properties of the designed vehicle model. In simulations involving nose length, when the nose length of the basic shape increases, the aerodynamic drag is reduced. Interestingly this tendency is a direct linear relationship. Extension of the nose length of the bio-model results in lower aerodynamic drag, and similar results have been reported in other studies of smooth nose shapes too. When the eye-ridge was removed there was a tendency for a steady rate of change in the aerodynamic drag. Following the simulation results of their aerodynamic properties, it was concluded that the eye-ridge feature was present purely to accommodate the eye, and that it should not be incorporated into high-speed train designs. The decreasing variance between the maximum drag coefficient values with the minimum coefficient value becomes smaller as the nose angle decreases.

The geometrical parameters that mathematically define a shape are widely used in solving the problem of nose shape optimization of high-speed trains. However, their mathematical representation is almost impossible if a complex atypical shape is applied to the nose by a biomimetic design approach. Thus the deformation and optimization of the applied basic shape is almost impossible unless the current method provides controllable geometrical parameters to describe the complex atypical shape. Moreover there is a point often missed regarding shape modification. Shape verification and validation is necessary because designers use a shape as output for showing adaptations. The evolutionary process of one species is equal to the cumulated process of all adaptations, and in biomimetic design, designers apply morphological advantages to the design object to satisfy design requirements. In other words, 'shape' and 'morphological advantages' are synthetic outputs of the evolutionary processes of each sub-feature. Nevertheless, there is no chance to reflect the traits of specific sub-features that directly colligate with evolutionary shape modification. That is why we apply the sub-features as shape parameters for the shape modification to verify and validate the chosen shape. The simulation results, achieved by deformation of these parameters, indicate that modification of some sub-features could improve results beyond that of the initial shape of the chosen bio-model. The verification and validation of each sub-feature should be conducted to improve and optimize the chosen bio-model. The research findings include the necessity of close study on sub-features that are revealed to be inappropriate for application in the design of the nose shape of high-speed trains. Specific reasons for the inappropriateness or appropriateness of sub-features were not addressed in this research. Furthermore, the possibility that there is another, superior shape that is more appropriate for the nose part of high-speed trains is not negligible. Further research is needed for improving the search process that precedes selection of a bio-model.

References

[1] R. Bannasch, in: H.-J. Bullinger (Ed.), Bionics, in Technology Guide, Springer-Verlag, Berlin, 2009, pp. 178–183.
[2] I.K. Bartol, M.S. Gordon, M. Gharib, J.R. Hove, P.W. Webb, D. Weihs, Flow patterns around the carapaces of rigid-bodied, multi-propulsor boxfishes, Integr. Comp. Biol. 42 (5) (2002) 917–980.
[3] I.K. Bartol, M. Gharib, D. Weihs, P.W. Webb, J.R. Hove, M.S. Gordon, Hydrodynamic stability of swimming in ostraciid fishes: role of the carapace in the smooth trunkfish Lactophrys triqueter (Teleostei: Ostraciidae), J. Exp. Biol. 206 (2003) 725–744.
[4] I.K. Bartol, M. Gharib, P.W. Webb, D. Weihs, M.S. Gordon, Body-induced vertical flows: a common mechanism for self-corrective trimming control in boxfishes, J. Exper. Biol. 208 (2005) 327–344.
[5] J.M. Benyus, Biomimicry: Innovation Inspired by Nature, Harper Perennual, New York, 2002.
[6] Q. Bone, R.H. Moore, Biology of Fishes, Taylors & Francis, New York, 2008.
[7] F.L. Bookstein, Landmarks methods for form without landmarks: Morphometrics of group differences in outline shape, in: Proceedings of the workshop on Mathematical Methods in Biomedical Image [7] Analysis (MMBIA) 1996, San Francisco, US, 1996, pp. 279–289.
[8] R. Boyd, P.J. Richerson, Culture and the Evolutionary Process, University of Chicago Press, Chicago, 1995.
[9] D. Bush, The Streamlined Decade, George Braziller Inc., New York, 1975.
[10] M. Cardillo, Some applications of geometric morphometrics to archaeology, in: A.M.T. Elewa (Ed.), Morphometrics for Nonmorphometricians of Lecture Notes in Earth Sciences, vol. 124, Springer-Verlag, Berlin, 2010, pp. 325–344.
[11] W.J. Caldecutt, D.C. Adams, Morphometrics of trophic Osteology in the threespine stickleback, Gasterosteus aculeatus, Copeia 1998 (4) (1998) 827–838.
[12] R.H. Carlson, Biology is Technology, Harvard University Press, Cambridge, 2010.
[13] S.B. Carroll, J.K. Greineir, S.D. Weatherbee, From DNA to Diversity, Blackwell Publishing, Oxford, 2005.
[14] C. Cogdell, Products or bodies? Streamlined design and eugenics as applied biology, Design Issues 19 (1) (2003) 36–53.
[15] M.H. Dickinson, Bionics: biological insight into mechanical design, Proc. Natl. Acad. Sci. USA (PNAS) 96 (25) (1999) 14208–14209.
[16] J.-P. Dujardin, in: M. Tibayrenc (Ed.), Modern Morphometrics of Medically Important Insects, in Genetics and Evolution of Infectious Diseases, Elsevier, Cambridge, 2011, pp. 473–501.
[17] M. Givoni, Development and impact of the modern high-speed train: a review, Transport Rev.: A Transnat. Transdiscip. J. 26 (5) (2007) 593–611.
[18] P. Hammerstein, J.R. Stevens, in: P. Hammerstein, J.R. Stevens (Eds.), Six reasons for invoking evolution in decision theory, in Evolution and the Mechanisms of Decision Making, The MIT Press, Cambridge, 2012, pp. 1–17.
[19] W.-H. Hucho, Aerodynamics of Road Vehicles: From Fluid Mechanics to Vehicle Engineering, Society of Automotive Engineers, Warrendale, 1998.
[20] M. Kawakami, K.-I. Yamamura, Cranial bone morphometric study among mouse strains, BMC Evol. Biol. 8 (73) (2008). 11 pages.
[21] K.M. Kim, The new model construction of design knowledge for exterior of high-speed train's nose on the base of Ontology, Ph.D. Thesis, Seoul National University of Technology, Seoul, Republic of Korea, 2008, 324 pages.
[22] Y.-H. Kim, Y.Y. Sun, S.B. Zhang, An initio calculations predicting the existence of an oxidized calcium dihydrogen complex to store molecular hydrogen in densities up to 100 g/L, Phys. Rev. B 79 (11) (2009). 5 pages.
[23] W.J. Kindlein, A.S. Guanabara, Methodology for product design based on the study of bionics, Mater. Des. 26 (2005) 149–155.
[24] A.M. Lawing, P.D. Polly, Geometric morphometrics: recent applications to the study of evolution and development, J. Zool. 280 (2009) 1–7.
[25] C. Lichtenstein, F. Engler, Streamlined: A Metaphor for Progress, Princeton University Press, Princeton, 1995.
[26] Y.H. Meguru, The development and action of Shinkansen 500 series, Railway J. Jpn. (2008) 23–27.
[27] P. Mitteroecker, P. Gunz, Advances in geometric morphometrics, Evol. Biol. 36 (2) (2009) 235–247.
[28] K.J. Parsons, B.W. Robinson, T. Hrbek, Getting into shape: an empirical comparison of traditional truss-based morphometric methods with a newer geometric method applied to New World Cichlids, Environ. Biol. Fishes 67 (4) (2003) 417–431.
[29] M.B. Ptacek, S.J. Hankinson, in: M. Ruse, J. Travis (Eds.), The Pattern and Process of Speciation, in Evolution, The Belknap Press of Harvard University Press, Cambridge, 2009, pp. 177–207.
[30] R.S. Raghunathan, H.-D. Kim, T. Setoguchi, Aerodynamics of high-speed railway train, Prog. Aerosp. Sci. 38 (6–7) (2002) 469–514.
[31] G. Rivera, A.R.V. Rivera, E.E. Dougherty, R.W. Blob, Aquatic turning performances of painted turtles (Chrysemys picta) and functional consequences of a rigid body design, J. Exper. Biol. 209 (2006) 4203–4213.
[32] D.E. Slice, Modern Morphometrics in Physical Anthropology, Kluwer Academic/Plenum Publishers, New York, 2005.
[33] H. Stachelberger, P. Gruber, C. Gebeshuber, in: P. Gruber (Ed.), Biomimetics: Its Technological and Societal Potential, in Biomimetics – Materials, Structures and Processes, Springer-Verlag, Berlin, 2011, pp. 1–6.
[34] R.S. Tu, M. Tirrell, Bottom-up design of biomimetic assemblies, Adv. Drug Deliv. Rev. 56 (2004) 1537–1563.
[35] S.S. Vattam, M.E. Helms, A.K. Goel, Compound analogical design: Interaction between problem decomposition and analogical transfer in biologically inspired design, in: Proceedings of the Design Computing and Cognition 2008, Atlanta, US, 2008, pp. 337–396.
[36] S. Vogel, K.K. Davis, Cats' Paws and Catapults: Mechanical Worlds of Nature and People, Norton, London, 2000.
[37] J.A. Walker, M.A. Bell, Net evolutionary trajectories of body shape evolution within a microgeographic radiation of threespine sticklebacks (Gasterosteus aculeatus), J. Zool. 252 (3) (2000) 293–302.
[38] D. Weihs, Stability versus maneuverability in aquatic locomotion, Integr. Comp. Biol. 42 (1) (2002) 127–134.
[39] T. Wynn, F. Tierson, Regional Comparison of the Shapes of Later Acheulian Handaxes, Am. Anthropol. 92 (1990) 73–88.
[40] X.-G. Zhang, H. Zhang, B.-X. Xiong, Subspecies validity for genus Culter based on morphometrics analysis, Environ. Biol. Fishes 28 (2009) 193–201.
[41] M.T. Zischke, S.P. Griffiths, I.R. Tibbetts, J.G. Lester, Stock identification of wahoo (Acanthocybium solandri) in the Pacific and Indian Oceans using morphometrics and parasites, ICES J. Mar. Sci. 70 (1) (2013) 164–172.

Please cite this article in press as: S.-J. Kim, J.-H. Lee, Parametric shape modification and application in a morphological biomimetic design, Adv. Eng. Informat. (2014), http://dx.doi.org/10.1016/j.aei.2014.09.006