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Using rapid prototypes for functional evaluation of evolutionary product designs

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Abstract

Purpose – To illustrate the benefits of using the empirical similitude method when creating scale models with rapid prototyping processes, particularly in the context of evolutionary product design.

Design/methodology/approach – Apply the empirical similitude method in two experimental examples. Utilize rapid prototyping processes to create scale models. Both examples are based on the context of evolutionary product design. For one example, evaluate accuracy of empirical similitude results as compared to traditional similitude.

Findings – The first experimental example showed improved accuracy in the empirical similitude results as compared with traditional similitude. The second experimental example illustrated an effective approach for applying the empirical similitude method to a realistic product evolution.

Research limitations/implications – Limited to two experimental examples. Examples involve a single prototyping process (selective laser sintering). Does not cover limitations of the empirical similitude method.

Practical implications – The approach provides for an effective way of utilizing rapid prototypes to predict the functional behavior of an evolutionary product. Rapid prototypes are readily available, but are rarely used in evaluating product function, due to limitations in part sizes and material properties.

Originality/value – This paper provides a practical way of utilizing rapid prototypes to predict the functional behavior of a product through scale models. It also illustrates the proposed method with two experimental examples.

Keywords Rapid prototypes, Product design

Paper type Research paper

Introduction

Prototypes represent a powerful means of evaluating new product designs. Such evaluations are generally accomplished through a combination of both virtual and physical prototypes. A *virtual prototype* is defined as a computer model or simulation that aids in the evaluation of a product design. Virtual prototypes are often used to extract similar information about a product as that obtained from physical models (Chua *et al.*, 1999). Virtual prototypes can, at times, even provide more insight into a design than is available from a physical model (e.g. evaluation of various states of stress throughout a product). The benefits of virtual prototypes, including low cost and short cycle times, has lead to a push by many companies to replace at least some physical prototypes with virtual prototypes (Ullman, 1997).

Despite advancements in virtual modeling, physical prototypes still play a vital role in the evaluation of many new product designs. The role of physical prototypes is particularly important in situations where virtual models have not been fully developed or properly refined. For many design problems, virtual and physical prototypes complement one another. For example, a virtual prototype will often evolve through an iterative process such as the following:

1. a virtual prototype is created and evaluated;
2. a physical prototype is created and tested;
3. the behavior of the virtual and physical prototypes is compared;
4. the virtual prototype is refined to match the physical prototype more closely; and
5. the process is repeated until the virtual prototype is properly refined.

Once a virtual prototype has been properly refined, an effective and extensive exploration of the design space can be performed.

The integration of this prototyping process into product design is shown in Figure 1. As shown in the figure, evaluation of virtual and/or physical prototypes leads to iterative updates to the description of the product. Of course, actual design processes differ in the number and type of prototypes used (i.e. company A may rely more heavily on virtual prototypes, while company B uses primarily physical prototypes), but the general process shown in Figure 1 is representative of a typical design process. Figure 1 also shows the progression of physical prototypes from engineering or experimental prototypes through pre-production prototypes as the design matures and approaches production (Ullrich and Eppinger, 2000).

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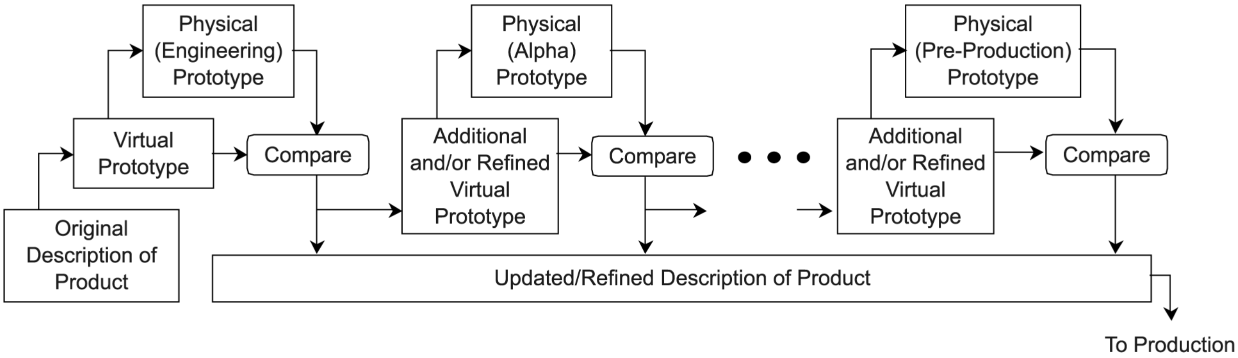
Figure 1 Typical prototyping process in product design

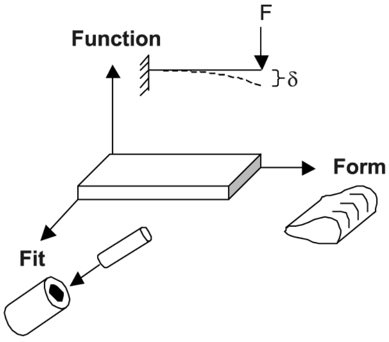


The cost and cycle time of the prototyping process shown in Figure 1 can be significantly reduced through the use of rapid prototypes in place of traditional prototypes. The use of rapid prototypes in product design has been credited with reducing development costs by as much as 40-70 percent (Dulieu-Barton and Fulton, 2000). The opportunity for such reductions in development time and cost is particularly apparent for products that involve complex geometry. The increased benefit for products with complex geometry arises from the fact that fabrication time for rapid prototypes (unlike that for traditional prototypes) is relatively insensitive to geometrical complexity. The ability to effectively evaluate products using rapid prototypes in place of traditional prototypes has the potential of significantly cutting development times and cost.

Several challenges exist, however, in replacing traditional prototypes with rapid prototypes in the product development process. Prototypes (of any type) are used to evaluate the fit, form, and function of product designs. The current state of RP technology provides for accurate evaluation of fit and form characteristics of a product, but allows only limited evaluation of functional behaviors (Figure 2) (Dornfeld, 1995). In order to replace traditional prototypes with rapid prototypes in the product development process, the level of functional information that can be obtained from rapid prototypes must be increased.

The limited ability of RP parts to be used for functional evaluation of a product stems primarily from limitations in available part sizes and material properties in current RP systems. Two basic approaches exist for overcoming these limitations:

Figure 2 Capability of RP in product evaluation



(1) improve the base materials and/or processes in order to increase the range of available material properties and part sizes; and
(2) correlate behaviors of existing materials and part sizes to desired materials and part sizes through similitude techniques.

Significant research has been dedicated to both of the approaches mentioned above. The first approach deals with improving and expanding RP systems, while the second approach seeks to utilize the systems that are already in place. While the first approach provides a more direct means of obtaining functional information on a part, the second approach is more flexible in its ability to predict behavior for a wide range of different product sizes and materials. The second approach is the one taken for this research.

It should be noted that the two approaches mentioned above refer to the direct use of RP parts to evaluate function. Secondary processes, such as investment casting, represent alternative approaches to evaluate function through the use of RP parts. Such secondary approaches are not considered in this paper.

Similitude techniques

The most common similitude technique is known as dimensional analysis or the traditional similitude method (TSM). The TSM uses dimensional information to develop constant scale factors that relate the behavior of two similar systems. The scale factors are developed by recasting the functional relationship of a system into dimensionless form, as follows:

$$g(d_1, d_2, \ldots, d_n) = 0 \Rightarrow f(\pi_1, \pi_2, \ldots, \pi_N) = 0 \qquad (1)$$

where d_j are dimensional parameters, π_i are dimensionless products, and $N < n$. If we consider two similar systems (a product system, p, and a model system, m) the dimensionless form of the functional equations can be written as:

$$f(\pi_{p,1}, \pi_{p,2}, \ldots, \pi_{p,N}) = 0 \quad f(\pi_{m,1}, \pi_{m,2}, \ldots, \pi_{m,N}) = 0 \qquad (2)$$

or, in terms of a particular parameter of interest, X, as:

$$\begin{aligned} \pi_{p,X} &= f(\pi_{p,1}, \pi_{p,2}, \ldots, \pi_{p,N-1}) \\ \pi_{m,X} &= f(\pi_{m,1}, \pi_{m,2}, \ldots, \pi_{m,N-1}) \end{aligned} \qquad (3)$$

For the two systems described by equation (3), the TSM states that $\pi_{p,X} = \pi_{m,X}$ (which is known as the prediction equation) if $\pi_{p,i} = \pi_{m,i}$ (which is known as the similarity constraints) for all $i=1, 2, \ldots, N-1$. The constant scale factors used in the TSM are derived directly from the prediction equation and the similarity constraints described above. (For more details on the TSM, refer Barr (1979), Langhaar (1951), or Szirtes (1998).)

If, for example, the deflection of a model cantilever beam (*m*) is used to predict the deflection of a product beam (*p*), the TSM can be used to create the following prediction equation,

$$\frac{\delta_m}{h_m} = \frac{\delta_p}{h_p} \tag{4}$$

subject to the following similarity constraints:

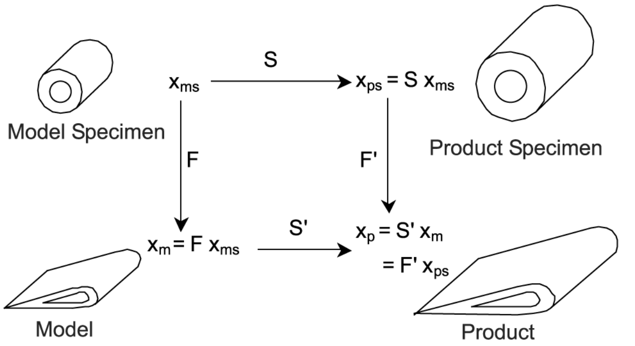
$$\frac{w_m}{h_m} = \frac{w_p}{h_p}, \quad \frac{F_m}{h_m^2 E_m} = \frac{F_p}{h_p^2 E_p}, \quad \frac{L_m}{h_m} = \frac{L_p}{h_p} \tag{5}$$

where δ is the beam deflection, h the beam height, w the beam width, F the applied force at the end of the cantilever beam, E the modulus of elasticity, and L the beam length (Dutson, 2002). If all of the similarity constraints described in equation (5) are satisfied, the two systems are said to be *well scaled*. If any of the similarity constraints are violated, however, the two systems are said to be *distorted*. Application of the TSM to distorted systems produces inaccurate results.

Several features of RP systems can often lead to system distortions and, consequently, inaccurate results from the TSM. For example:

- Rapid prototypes are often produced with polymeric materials that have, to some extent, nonlinear stress-strain curves. If the product system has a linear stress-strain curve, and the elastic modulus is one of the parameters in the similarity constraints, the two systems are distorted.
- The number of materials available for RP parts is quite limited. The similarity constraints may call for a required material property ratio (such as E_m/E_p) that is not physically possible with the limited values of E_m that are available from RP systems. In such situations, the two systems will again be distorted.
- A particular RP build may produce material properties that are different from published values. Variation in material properties may result from different machine settings, different environmental conditions, etc. If the material properties of an RP part are different from the expected or published values, the system again becomes distorted.
- Rapid prototypes are often produced in a layer-by-layer additive process. Such processes tend to produce orthotropic or transverse isotropic material structures. If the product system has an isotropic material structure and the model has an orthotropic structure, the systems will be distorted with respect to material structure.

Figure 3 Empirical similarity method



Source: Cho (1999)

In many instances rapid prototypes cannot be used in the TSM to accurately predict product performance because of the distortions described above. For this reason, an empirical similitude method (ESM) was developed to overcome such limitations in the TSM and allow for broader use of rapid prototypes in predicting the functional behavior of a product. The fundamental concept of the ESM is shown in Figure 3. The ESM is able to correlate distorted systems by utilizing empirical data from a simplified specimen pair. The model specimen (MS) shown in Figure 3 is a geometrically simplified version of the model, and the product specimen (PS) is a geometrically simplified version of the product. The ESM uses measured values from the MS, PS, and the model to predict the behavior of the product. The basic assumptions of the ESM are as follows (refer Wood, 2002; Dutson *et al.*, 2003).

- The model and MS are tested to determine the state variation that is caused by changes in geometric shape, or *form*. A *form transformation matrix*, F is derived that represents the variation in the state vector x that is caused by the change in geometric shape between the model and the MS.
- The MS and the PS are tested to determine the state variation that is caused by changes in material properties, loading conditions, and size (with no change in geometric shape). A *scale transformation matrix*, S is derived that represents the variation in the state vector x that is caused by changes in size, material properties, and loading conditions, independent of geometric shape.

The state of the product is predicted by multiplying the state of the model by S' or by multiplying the state of the product specimen by F', as shown in Figure 3. A basic assumption of the ESM is that $S=S'$ and $F = F'$, or, in other words, that S and F are *independent*. Details about how to derive the transformation matrices S and F are given in Dutson (2002) and Cho (1999).

The capabilities of the ESM have been demonstrated by Cho (1999). While the potential of the ESM in predicting product behavior is quite promising, the practicality of creating three distinct systems (viz. a model, a MS, and a PS) in order to predict the behavior of the product may reasonably be brought into question. There are, however, situations that lend themselves very well to the ESM technique. One such situation involves evolutionary product design.

Product evolution

Product evolution represents a major component of product development efforts. Rarely is a product developed entirely from scratch; rather, products are more often designed as variations of existing products. The ESM technique is very well suited for product evolution since the previous version of the product can often be used as the PS for the new design. The functional performance of the new design can be predicted with the ESM as follows.

- Use the current product as the PS for the new design.
- Create a rapid prototype of the current product with the (already existing) solid model of the current design. This rapid prototype can be used as the model specimen.
- Modify the solid model to reflect the evolved design. Create a rapid prototype of the evolved design. This rapid prototype can be used as the model.
- Use the ESM, along with the model, MS, and PS described above, to predict the functional behavior of the new design.

The approach described above is very simple to implement since the model and the MS can be created quickly with RP techniques, and the PS is already available. This approach may be easier to implement than the TSM in many instances since details about the governing parameters and specific material properties need not be determined *a priori* (as is required in the TSM).

Two experimental examples are presented in the following sections that illustrate the use of the ESM for evolutionary product design. The first example, which involves the deflection of a cantilever beam under a concentrated load, is used simply to illustrate the ESM procedure and how it might be applied to evolutionary design. The second example illustrates the use of the ESM in evaluating an evolutionary headphone design.

Experimental evaluation of static deflection

The product whose behavior was to be predicted in this case was a cantilever beam with six evenly spaced holes along its length. The dimensions of the beam are shown in Figure 4. The product beam was made of 6061 aluminum. A total load of 13.34 N was applied 127 mm from the fixed end. The static deflection of the beam at the point where the load was applied was monitored at five different increments of load (up to 13.34 N). The state vector of interest was, therefore, a deflection vector with five entries, each of which corresponds to a particular load.

The goal of this experiment was to use RP model beams with the ESM procedure to predict the deflection of the product beam. A polymeric material called Duraform™ was used in the selective laser sintering (SLS) process to create the model beams. The PS was simply an aluminum beam with the same dimensions as the product, but with no holes. A product beam was constructed in order to establish the actual deflection of the product beam and demonstrate the relative errors in the TSM and ESM techniques. For convenience, the size of the model beams was chosen to be the same as that of the product beam. The overall setup for this experiment is shown in Figure 5 (note in Figure 5 *MS* refers to *model specimen* and *PS* refers to *product specimen*).

The beams were prepared for testing by fixing (i.e. clamping) one end of the beam and applying the load 127 mm from the fixed end. Calipers were mounted to a stand and were used to measure the static deflection of the beam at each increment of the load. The experimental setup is shown in Figure 6.

The force that was applied to the model beam (as well as to the MS) was determined from the TSM scale factors. The prediction equation and similarity constraints for the deflection of a cantilever beam were shown earlier (refer equations (4) and (5)). If we define a scale factor K as the ratio of a product parameter x_p to the corresponding model parameter x_m, then we can rewrite equations (4) and (5) in the following form:

$$K_\delta = K_h \quad \text{if} \quad K_w = K_h, \quad K_F = K_h^2 K_E, \quad \text{and} \quad K_L = K_h \qquad (6)$$

The scale factors and parameter values for both the model and the product systems are shown in Table I (note that the values shown in Table I are the *ideal* values upon which the TSM scale factors are based; any deviation from these ideal values in the actual experiment constitutes a source of model distortion).

The deflection results for the model and product beams are shown in Table II. (Note that the actual weights applied to the beams are close to, but not exactly equal to, those prescribed by the TSM scale factors. This was due to the fact that the exact weight values prescribed by the TSM were not readily available. This scenario produces the type of model distortion just described.) The deflection results in Table II are used to calculate both the TSM and the ESM prediction of beam deflection for each load increment. The predicted deflections are compared to the measured deflections of the product beam, and a percent error is calculated for each load increment. These results are tabulated in Table III and shown in Figure 7.

The results of this experiment show a significant improvement in the beam deflection predicted through the ESM technique over that predicted through the TSM technique. Two potential sources of distortion that may have contributed to the error in the TSM technique include: first, the applied load was close to, but not exactly equal to, that prescribed by the TSM; and second the material properties of the model beams may have been different from the published values. The second factor is likely the most significant contributor to the TSM error in this case.

Figure 4 Dimensions of product beam

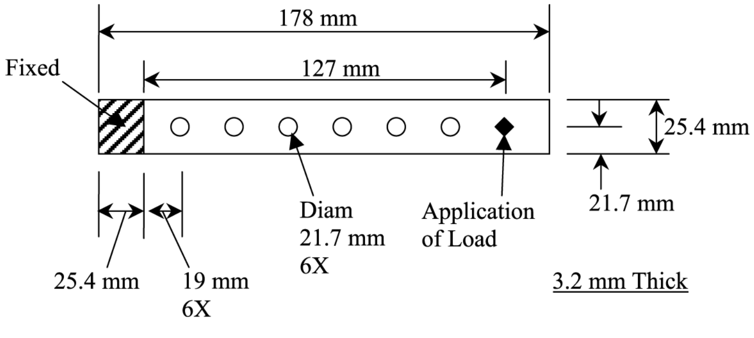


Figure 5 ESM setup for beam experiments

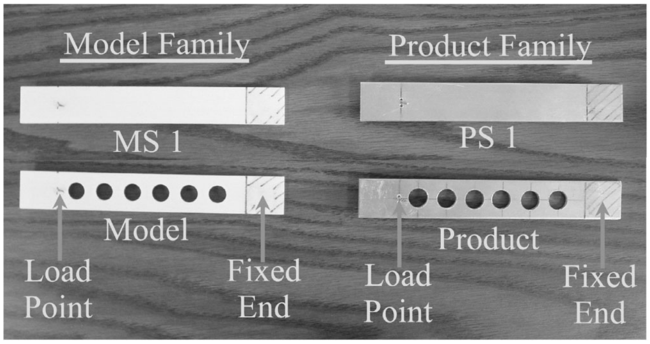


Figure 6 Experimental setup for beam experiments

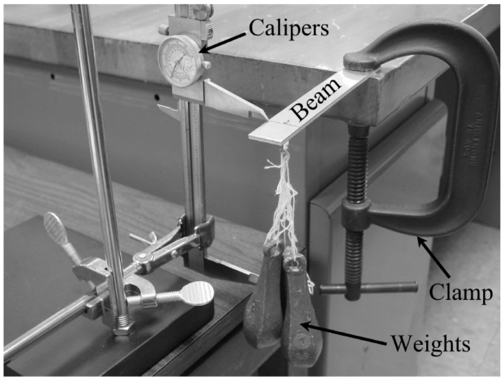


Table I Parameter values for beam experiment

	TSM scale factor ($K = x_p/x_m$)	Value of product parameters (x_p)	Value of model parameters (x_m)
Applied force (*F*)	46.1	13.34 N	0.289 N
Beam length (*L*)	1.00	177.8 mm	177.8 mm
Beam width (*w*)	1.00	25.4 mm	25.4 mm
Beam height (*h*)	1.00	3.2 mm	3.2 mm
Young's modulus (*E*)	46.1	70 GPa	1.5 GPa

Table II Deflection results for cantilever beams

Model family			Product family		
Applied force (N)	δ_{ms1} (mm)	δ_{model} (mm)	Applied force (N)	δ_{ps1} (mm)	$\delta_{product}$ (mm)
0.069	0.66	0.97	3.003	0.48	0.69
0.139	1.22	2.13	6.005	1.04	1.42
0.209	1.91	3.07	8.852	1.55	2.18
0.278	2.51	4.04	10.542	1.78	2.54
0.334	3.15	5.21	13.434	2.26	3.25

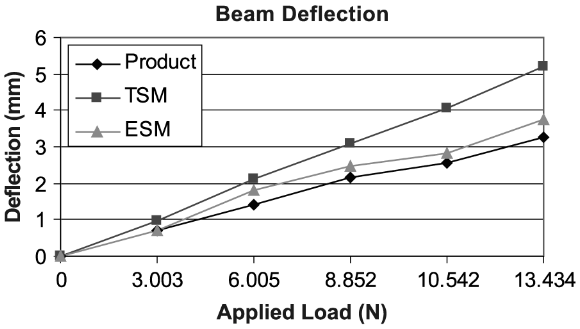
The potential sources for the error in the ESM prediction are presented in Dutson *et al.* (2003).

It should be noted that, not only did the ESM technique produce superior prediction results but it was also easy to implement. In the context of evolutionary design, one could assume that the PS (the aluminum beam with no holes) was already available. The setup for the ESM technique then requires simply the creation of a model and a MS (from an RP process in this case). Detailed knowledge of specific material properties and parameter values is not required as it is for the TSM.

Table III Deflection predictions for experimental study

Load increment	$\delta_{product}$	δ_{TSM}	Error TSM (percent)	δ_{ESM}	Error ESM (percent)
1	0.69	0.97	40.7	0.71	2.1
2	1.42	2.13	50.0	1.80	26.8
3	2.18	3.07	40.7	2.49	14.5
4	2.54	4.04	59.0	2.84	12.1
5	3.25	5.21	60.2	3.76	15.4
Average			**50.1**		**17.2**

Figure 7 Beam deflection results for experimental study



Evolutionary headphone design

Many styles of headphones exist on the market today. Several different styles are shown in Plate 1. The headphone design that will be modified in this example is shown in Plate 2. This product is used as the PS for the new design. Suppose that the existing product is to be modified so as to include a slot in the compliant member along the top of the headphone. The CAD solid models of the original design (which was reverse-engineered since the original CAD solid model was not available) and the modified design are shown in Figure 8. The CAD solid models shown in Figure 8 were used to create rapid prototype parts with the selective laser sintering process. The original design serves as the MS, while the modified design serves as the model.

Plate 1 Various headphone designs

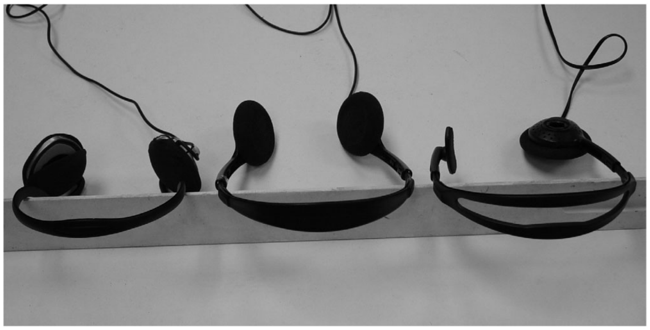


Plate 2 Current headphone design

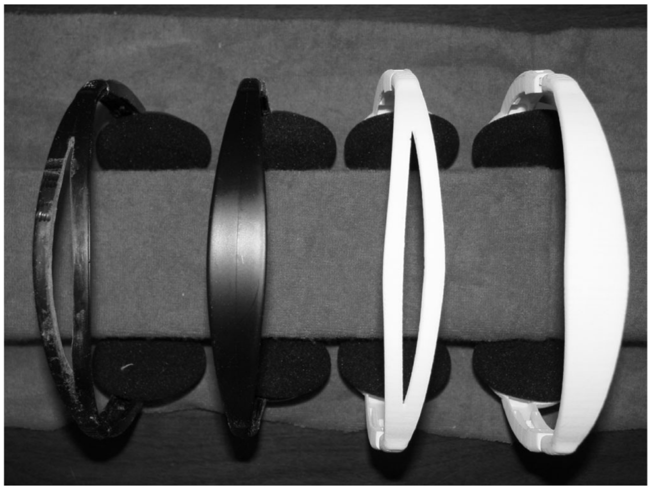
Figure 8 Solid models of headphone designs

Original Design Modified Design

In order to simulate the behavior of the product, a second headphone (of the existing design) was obtained and a slot was machined similar to that shown in Figure 8. The overall ESM setup for this problem is shown in Plate 3. Plate 3 shows, from left to right, the product, PS, model, and MS.

The behavior of interest in this case was the reaction force of the headphones under a specific displacement. The displacement was intended to represent the width of a human head. The reaction force produced from the given displacement (161 mm in this case) was recorded for each set of headphones shown in Plate 3. In this case, a single force value was obtained for each system, which results in state vectors with a dimension of *one* (i.e. a single value). The experimental setup is shown in Plate 4.

Plate 3 ESM setup for headphone redesign



The reaction force from an imposed 161 mm displacement was measured five times for each set of headphones shown in Plate 3. The measured values of force, along with the average value and standard deviation, are shown in Table IV. The average value was used as the state value for each system. The ESM prediction of product behavior is greatly simplified in this case by the fact that the state is represented by a single value. The ESM prediction of product behavior can be calculated as follows:

$$
\begin{aligned}
F_{\mathrm{ps}} &= SF_{\mathrm{ms}} \Rightarrow S = \frac{F_{\mathrm{ps}}}{F_{\mathrm{ms}}} = \frac{3.562\,\mathrm{N}}{2.355\,\mathrm{N}} = 1.512 \\
F_p &= SF_m = (1.512)(2.041\,\mathrm{N}) = 3.086\,\mathrm{N} \qquad (5\text{-}17) \\
\mathrm{Error}_{\mathrm{ESM}} &= \frac{3.086\,\mathrm{N} - 2.510\,\mathrm{N}}{2.510\,\mathrm{N}} \times 100\,\mathrm{percent} \\
&= 23.0\,\mathrm{percent}
\end{aligned}
$$

The relatively high error in the ESM prediction is attributed to the inaccuracy of the machined slot in the new "product" headphones. Since the slot was machined by hand, the dimensions of the slot were not as accurate as they would be in the actual product. In addition, machining the slot by hand

Plate 4 Experimental setup for headphone tests

Table IV Measurements of reaction force of headphones

Measurement	F_p (N)	F_{ps} (N)	F_m (N)	F_{ms} (N)
1	2.516	3.573	2.085	2.321
2	2.502	3.489	2.043	2.349
3	2.516	3.587	2.016	2.335
4	2.516	3.600	2.043	2.405
5	2.502	3.559	2.016	2.363
Average	**2.510**	**3.562**	**2.041**	**2.355**
Standard deviation	0.00767	0.04338	0.02825	0.03223

could have introduced stress concentrations that could affect the results. The example is effective, however, in demonstrating the power of the ESM approach in evolutionary product design.

Conclusions

The empirical similitude technique, or ESM, provides an effective means to evaluate evolutionary product designs. By using the existing version of the product as the PS, and by producing the model and MSs with RP techniques, the ESM can often be easier to implement than the TSM. The two experimental examples presented in this paper illustrate the benefits of the ESM. The ESM technique combined with modern RP capabilities hold great potential for improved product designs and reduced development costs and cycle times.

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