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Identification and codification of principles for functional tolerance design

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Tolerance design remains a key challenge in engineering design. The goal of the research presented in this article is to address this challenge through the identification and organization of novel tolerance design principles. These tolerance design principles are developed through a careful study of the literature, observation of commonly recurring tolerance solutions, and design strategies implied by the existing tolerance design literature. A key and novel contribution of the work presented in this article is that tolerance design is treated as a concurrent design problem. Tolerance design begins prior to assembly requirements and parameter design. Through the application of the principles presented here, tolerance design can be addressed through changes in product architecture and functionality. In addition, these principles provide a focus for developing new methodologies that will have high impact on engineering practice. These principles are formally organized to facilitate usage and extension. The usage and impact of these principles is shown through an example application to an original design problem. The design case study is an electric guitar pickup winder.

1. Introduction

Like Newton's falling apple, there are events whose occurrence follows some underlying, fundamental truth. An understanding of these fundamental truths is engineering power—the power to predict and perhaps control the outcome of events and situations. Newton's observation of the apple led to the notion of 'what goes up must come down'. The goal of the present paper is to explore and codify important fundamentals of what makes a design 'good' with reference to tolerance choices. In other words, is there some 'tolerance truth' to the design? Can some product be designed in such a way that the output performance is 'precise', but the input components are not?

What is presented here are tolerance design principles. Like any design principle, they provide a starting point for evaluating, improving, or generating a design. In addition, the crisp definition and discussion of these principles sets the stage for extending their qualitative nature to quantitative and complete theories for tolerance design, thus providing computational and precise tools to improve engineering design.

To motivate this work, the rest of this section briefly clarifies tolerance design in the context of product function and performance. Then, two critical issues in engineering design are briefly reviewed to place this work in the context of both current and future research. The first of these issues is the relationship between tolerance design,

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engineering design, and current research. It is important to develop basic tolerance design principles and to extend the notion of tolerance design beyond assembly requirements. Second, the role of design principles in both practice and design research is reviewed to provide a vision for the future extension of the principles presented in this paper.

1.1. The need for functional tolerance research

First, the notion of functional tolerance design needs to be clarified. Consider the general operation and function of a tennis ball. A tennis ball deemed acceptable for play by the US Tennis Association (1998) must bounce more than 53 cm, yet less than 58 cm, when dropped from 100 cm onto a concrete surface. Stated in a language generally more appropriate for engineering, the coefficient of restitution of a tennis ball is effectively $55.5\% \pm 2.5\%$ [1]. This requirement for a tennis ball is a functional tolerance: a functional tolerance is the acceptable specified performance variation in the function of a product, subsystem, or component.

The ball specification is part of a larger set of rules that govern the game of tennis. Included are specifications for the court, the net, and the racquet. Each of these components has a function, or functions, that must be performed with some minimal level of accuracy or performance. Specifying, or designing, these rules and regulations to achieve an acceptable, and repeatable, game of tennis is analogous to a critical task in engineering design. The question to the engineer is, given a product or system with some desired level of performance and associated performance, how can the product or system be designed to achieve this performance?

Guided by the need for consistency and uniformity, the functional tolerances of tennis have matured from decades of formal and informal trials. These trials have been conducted by players of varying skill levels on different court surfaces. Designers do not have the luxury of this type of product field testing and development. Even before prototypes are built, designers must recognize the effects of design decisions on performance variation. Unavoidable, or difficult to prevent, subsystem or component variation must be accounted for in the design solution, architecture, and final embodiment. When a prototype is built, the information gained from its construction, success, and failure must be maximized.

In practice, tolerance design is difficult and performed with varying degrees of success. In fact, it is noted in the literature that often tolerances are specified too small (Turner 1993). For example, a three-dimensional tolerance analysis of a fixed-disk data storage system showed that several tolerances could be eased, thus improving production rates and profit margins (Drake 1997). In this particular case, a more accurate model of the product geometry, and the manufacturing variability, enabled a deeper understanding of the existing tolerance specifications on disk-drive performance. That this tolerance analysis was not performed until the disk drive was already in production shows a lack of understanding of the importance of tolerances to the overall (in the sense of Taguchi) quality of a product (Soderberg 1993). More importantly, the use, and success, of tolerance re-design during product re-design clearly shows the need to integrate the notion of tolerance design into the very initialization of the design problem.

In comparison with other fields of engineering and engineering design, research tolerances have received very little theoretical treatment (Finger and Dixon 1989). A review of the tolerance design literature yields an interesting insight into the focus, activity, and success of tolerance design research. The history and effort of the tolerance research is primarily toward the end of the design process. The majority of tolerance research has been into tolerance communication (the language and representation of geometries) (Requicha and Chan 1986, Jayaraman and Srinivasan 1989, Willhelp and Lu 1992, Turner 1993, ANSI 1994, McAdams and Wood 1996, Srinivasan et al. 1996, Turner and Wozny 1996), tolerance specification to ensure assembly (Chase and Greenwood 1987, Bjørke 1989, Feng and Kusiak 1994, Gadallah and ElMaraghy 1994, Iannuzzi and Sandgren 1994), and manufacturing cost models for optimal tolerance allocation (Speckhart 1972, Spotts 1973, Soderberg 1993, Abdel-Malek and Asadathorn 1994). As the field of tolerance research has grown, the research efforts have moved from the final stages of the engineering design process toward the beginning. This research trend is an obvious outgrowth of the initial birth of tolerance design as it stemmed from mechanical drawing specifications and the need for interchangeable parts. In fact, much of the research being published remains focused on a tolerance design that ensures assembly.

Although there is much work remaining to be done in all areas related to tolerance design, the existing research has produced procedures, methods, and tools that the designer can use toward the end of a product design process. Thus, we pursue the development of tolerance design tools in less explored areas of the design process: we look toward the beginning of the design process. Because at the beginning of the design process, much of the information available about the design is qualitative, we look for qualitative tools: tolerance design principles.

1.2. The tolerance design principle niche in practice and research

As a definition, consider a design principle as ‘a recommendation or suggestion for a course of action to help solve a design issue’. This definition is adapted from the definition for a design guideline according to Nowack (1997). This definition is used here for a design principle as it is more consistent with how the term principle is used in design textbooks and monographs (Pahl and Beitz 1988, Ulrich and Eppinger 1995, Ullman 1997, Otto and Wood 2000).

As an example, shown in figure 1 is the design principle of direct and short force transmission path (Pahl and Beitz 1988). The principle states that if a force or moment is to be transmitted from one place to another with the minimum possible deformation, then the shortest and most direct force transition path is the best.

Although in general design principles provide the designer with qualitative rather than quantitative feedback, they provide the practicing design community with a valuable resource of knowledge; design principles allow knowledge-based design. In the research community, design principles also serve as a valuable resources and pointer toward future research needs.

In the same way, the observation of some event serves as the first step of the scientific method [2] design principles serve as the catalyst for developing complete methodologies and theories for engineering design. An example of the progression from principle to mathematical formulation is depicted in figure 2. In this figure, an analogy is made between the development of generative tools for engineering design and the development of basic knowledge based on the scientific method. As a specific example, Taguchi’s (1986) robust design is shown. Because of its benefit to tolerance design, Taguchi’s robust design and the associated approach to tolerance design is particularly complimentary to the discussion at hand.

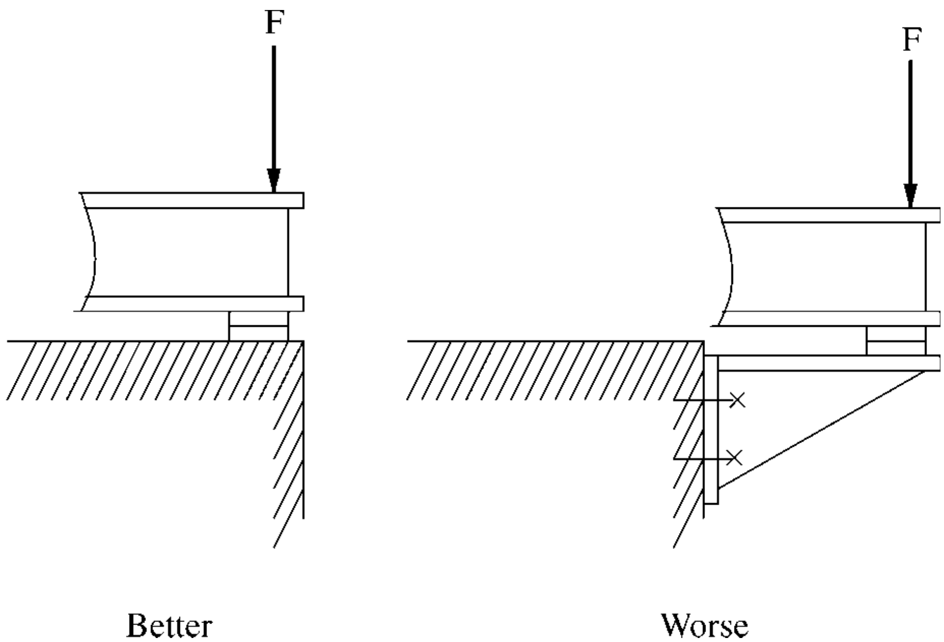

Figure 1. Illustration of the principle of direct and short force transmission.

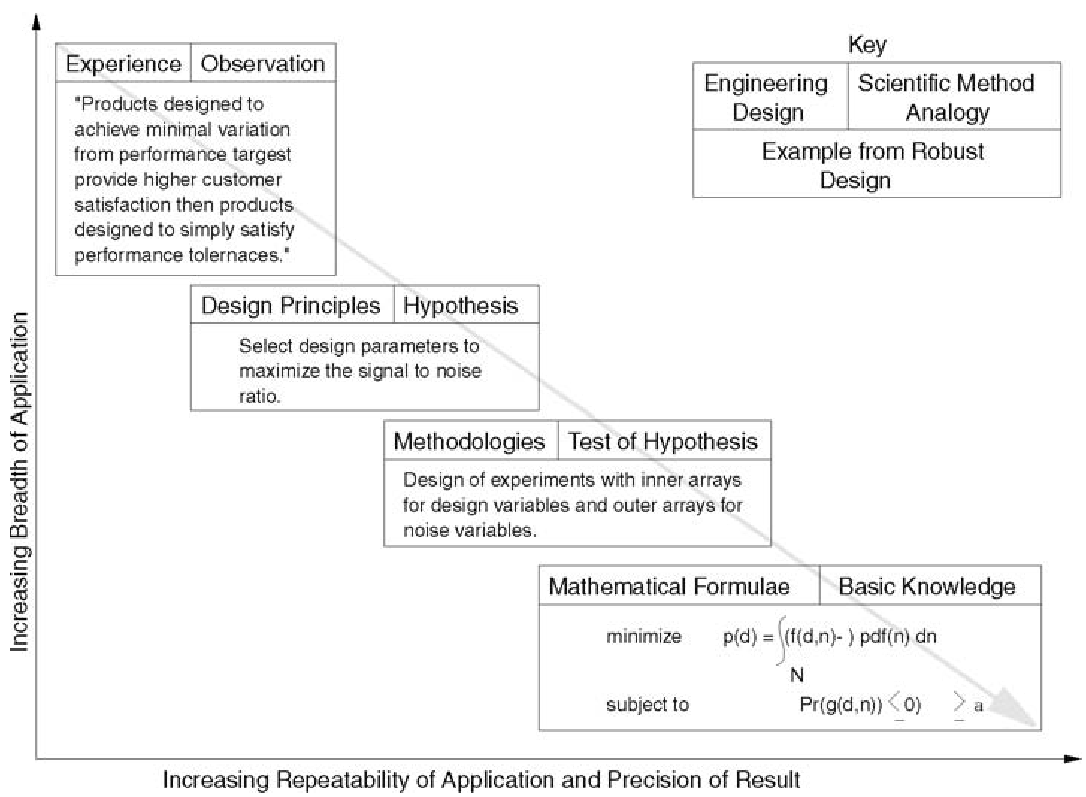

Figure 2. The maturation of tools for engineering design as they move from observation to mathematically or empirically based tools.

Thus, tolerance design principles serve two critical niches to tolerance design:

1. They enable engineers to access the experience of others and thus produce 'good' designs without having to learn through first-hand trial and error.
2. They serve as a pointer to an area in need of further development and design research.

With this in mind, we proceed to the presentation of the tolerance design principles. Following that is a design case study that shows the application of some of the design principles applied in an original design exercise.

2. The tolerance design principles

These principles are based on the observation of some best or past practice that leads to good tolerance design. The central truth that these principles explain, or more appropriately attempt to store and provide for re-use, is that the tolerance problem can often be solved without undue dependence on component precision. It can be solved by subtle, although significant, design changes.

These principles are presented without regard to their potential impacts on non-tolerance-related metrics of the design. In some cases, the principles will point to a tolerance design solution that has a negative impact on the design in some other way. The decision as to what is more important is up to the designer based on customer needs and other constraints. Evaluating these types of design decisions is beyond the scope of the present article.

Some of these principles are concerned with the product or object layout and detail design, and thus are largely independent of a manufacturing process. Other principles are directly related to a manufacturing process. As a first stage of organization for usage, the tolerance design theories are organized into three different categories. The first is system tolerance design principles, which are the most general of the principles and are useful when applied very early in the design process. The second category is parameter tolerance design principles, which focus on the relationship between parameter design and tolerance design. Here, parameter design refers to setting the target values of the critical features that the designer specifies to control performance. The final category is manufacturing tolerance design principles, which focus on the relationship between tolerance issues and associated manufacturing and assembly techniques.

These tolerance design principles are developed through a careful study of the literature, observation of commonly recurring tolerance solutions, and design strategies implied by the existing tolerance design literature. Although these tolerance design principles are also often general design principles, design principles that are completely general, such as 'simpler is better', have been intentionally left out. The tolerance design principles are given a sometimes whimsical name in an attempt to conjure up an implementation of the tolerance design solution and make them easy to remember.

2.1. System tolerance design principles

This class of tolerance design principles affects the form, layout, architecture, modularity, or solution principle of a given design. Applying these tolerance design principles to an existing solution may significantly change, or metamorphose, a design—that is the intent. Using these principles during design development also gives insight into potential tolerance problems early in the design stage.

2.1.1. Add adjustment, or feed forward tuning, parameters: the floor pan principle. If an overall performance measure is hard to achieve because of the stack ups of random variations, add an adjustment, or tuning parameter. Figure 3 shows the result of this principle applied to a concept for an automobile floor pan. The concept at the top of the figure has a variation in L that is the sum of the variations in each of the components. The concept in the bottom of the figure adds a tuning parameter to the lengths of the components. During assembly, the performance parameter L can be tuned to the correct length as specified by the jig. This principle is called feed forward because it only affects tunability during the manufacture or assembly stage. The principle does not point to solutions that respond to environmental stimuli.

2.1.2. Use analogue adjustments: the adjustable wrench principle, or the wheel alignment principle. The use of this principle is to add the ability to adjust key performance parameters. An example of this adjustment principle is the front-wheel alignment parameters on an automobile. To drive and steer correctly (straight) requires precise positioning of the front wheels. As suspension, frame, and steering components are manufactured and assembled, the stack-up error in camber, castor, and toe-in cause a car to steer poorly. To manufacture an automobile with enough precision that these tolerance stack-ups are small enough to allow satisfactory steering is not practical. To allow accurate and straight steering, adjustment parameters for castor, camber, and toe-in are designed into the steering and wheel mounting system that allow the alignment to be tuned. This philosophy is critically important in the approach of metamorphic tolerance design. The key notion here is the adding of functionality to the design to reduce the dependence on precision.

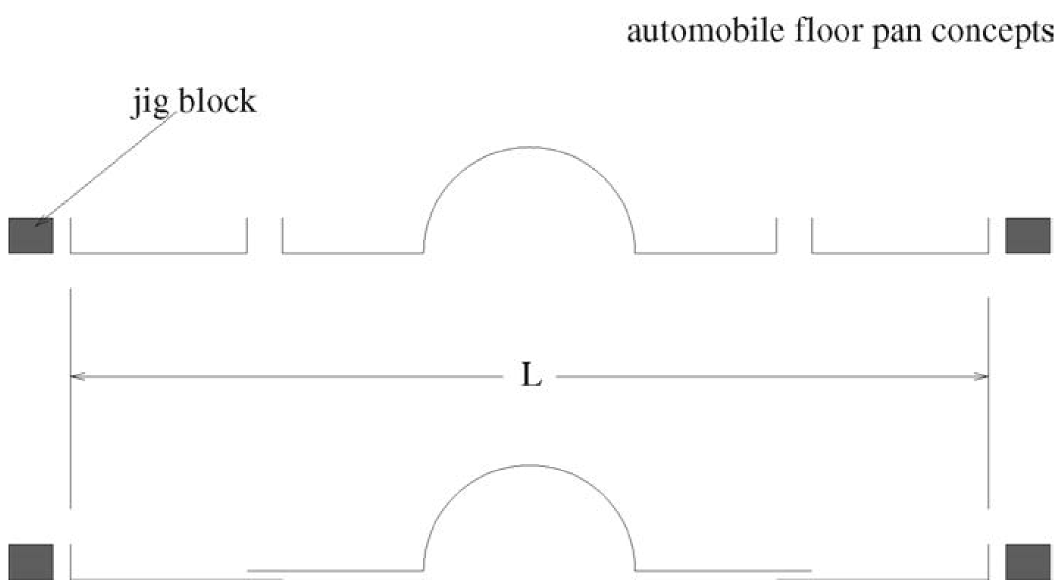

Figure 3. An example of adding a feed forward tuning parameter (Soderberg and Johannesson 1998).

Another application of this principle results in the concept of an adjustable wrench. In this case, the principle not only removes a dependence on precision, it increases the usefulness of the tool. In this case, it allows the device to overcome uncertainty in the environment in which it will be used. For example, a socket (for a socket wrench) is an inferior tolerance design because it depends on the size tolerances of the socket and the nut. An adjustable wrench is a better tolerance design because there is no size tolerance dependence. The tool continuously adjusts to fit the nut. An example of this tolerance design principle is illustrated in later figure 13 (section 4).

2.1.3. Add feedback tuning parameters: the precision by control principle. If a performance tolerance is difficult or impossible to meet because of environmental noise or other factors, add a control system to the device. Although such a control system is likely to increase the complexity of a product significantly, it may be the only option to achieve the needed performance. An example of this situation is the addition of a flywheel on the tape head in a video recorder. To ensure that the tape head rotates at a constant speed, a flywheel is attached to the head drive system. The flywheel evens out variations in input motor speed from power supply voltage variations and variations in the torque needed to drive the tape itself.

2.1.4. Preload elements to prevent free play: the bicycle spoke principle. Where the location or position of moving parts is important, they can be pre-loaded to prevent free play. An example of this solution is the return spring on a cam-follower system. Although the spring must exist for purely inertial reasons, a stiffer spring allows a rougher surface finish on the cam while still maintaining complete follower contact. Another classic example of this principle is the design of a spoked wheel, such as found on most bicycles. The variation of circularity of the wheel under load is much less than it would be if the spokes were not pre-stressed. Thus, the spokes can be reduced in mass, making the wheel strong, light, and round.

2.1.5. Distribute tolerance stack ups: the tile layout principle. The philosophy here is to add additional reference, or ground, points to performance parameters sensitive to a stack-up error. For example, when installing ceramic floor titles, layout lines are drawn on the floor for every 4×4 grouping of tiles. The tiles are adjusted and re-aligned to these lines as the floor is covered. Thus, the error in alignment and grout line gap never becomes larger than the stack up of three tiles: the stack-up error never grows noticeably large. This principle is illustrated in figure 4.

2.1.6. Reduce the number of part and module interfaces: the integrated hinge principle. If two parts do not have relative motion between them, re-design the part so that the same functionality is retained in one part. Applying this principle reduces the number of interfaces and fits. An example of this situation is the thin piece of plastic used as a hinge on many injection-moulded plastic containers, such as lunch boxes. For a standard two-piece hinge with a pin, there would be tolerances to ensure that the hinges from the box and lid mesh. In addition, there would be pin and hinge diameter clearance. With the integrated hinge, the pin-hinge tolerances are completely removed. This principle is illustrated in figure 5. Reducing interfaces is a specific result of ideas presented in Boothroyd and

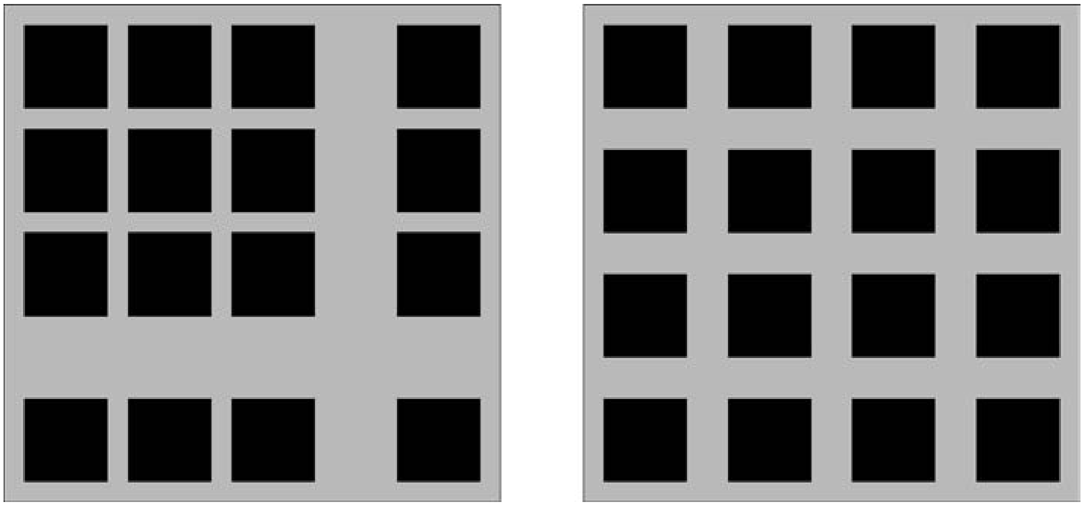

Figure 4. An illustration of the principle of distributing tolerance stack ups.

Dewhurst (1989) and Lefever and Wood (1996). It is an important design for assembly principle that applies to tolerance design.

2.1.7. Avoid unnecessary mechanical coupling: the violin finger board principle. If a system is less constrained, there are less tolerances to maintain and less tolerance errors to stack up. On a violin, the finger board connects only at the neck–body joint, thus floating above the top of the violin sound chamber. There is a functional need for a precision form tolerance in the finger board. If the finger board is connected to the body, a precision form tolerance is transmitted to the body through

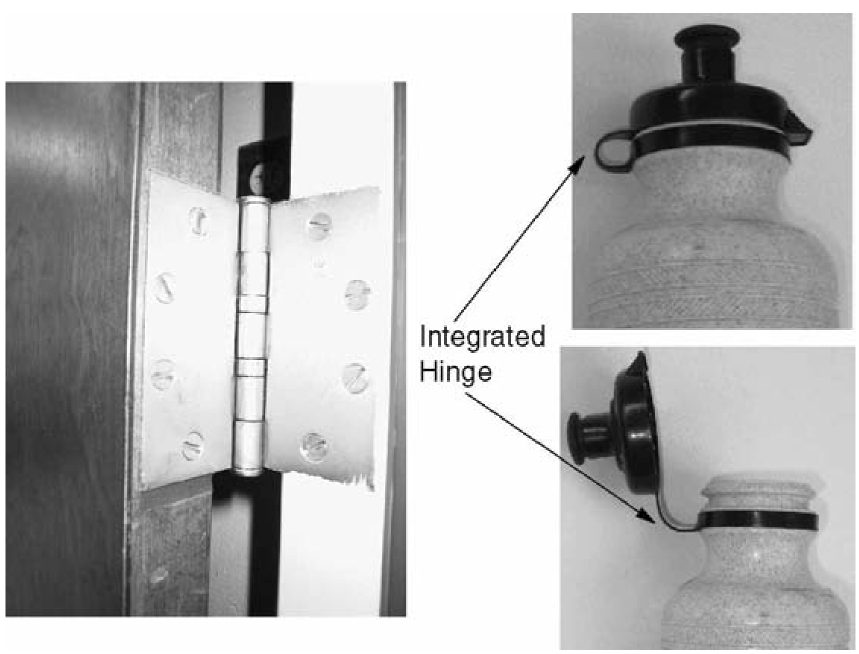

Figure 5. An illustration of the principle of reducing the number of part and module interest faces.

the finger board and body stack up when in fact it has no functional need for precision. By floating the fingerboard the need for a flatness or form tolerance on the sound board or violin body are alleviated. Using this tolerance design principle, the sound board and the finger board are not mechanically coupled; thus, changes in the flatness of the sound board do not affect changes in the flatness of the finger board. This principle is illustrated in figure 6. This principle is adapted from French's (1992) principle of kinematic design.

2.2. Parameter tolerance design principles

Parameter tolerance design principles are approaches to specifying parameters in such a way as to improve the performance of a system with respect to tolerances. The parameters are chosen in such a way that the general solution concept and form remains recognizably the same. Unlike the earlier tolerance design principles, no 'new' parameters are added.

2.2.1. Move the nominal set points: Taguchi's robust design principle. This principle is perhaps the most recognized of all tolerance design principles. As such, it has spawned an entire field of engineering design research. Simply put, the approach here is to choose the nominal design parameter values such that their effect on the variation of the performance is minimized. This principle is well developed and many examples of its usage exist. A complete discussion is not attempted here. For a modern and through presentation, and for a recent update of Taguchi's tolerance design, see Creveling (1997).

2.2.2. Choose elastic components for tight fits: the floor is never flat principle. This tolerance design principle is adapted from French (1992). When trying to obtain a tight, or precise, fit at an interface, allow one of the interfaces to be flexible and thus to elastically deform at the interface. An example of this principle is the flexible feet found on the bottom of many four legged chairs. As the flatness tolerance on the floor is large and difficult to predict, the chair provides a flexible interface. Thus, when seated in the chair, one does not rock awkwardly around. This principle is illustrated in figure 7.

2.3. Manufacturing tolerance design principles

These tolerance design principles attempt to match the design, architecture, components, and parameters with the manufacturing process. The principles of

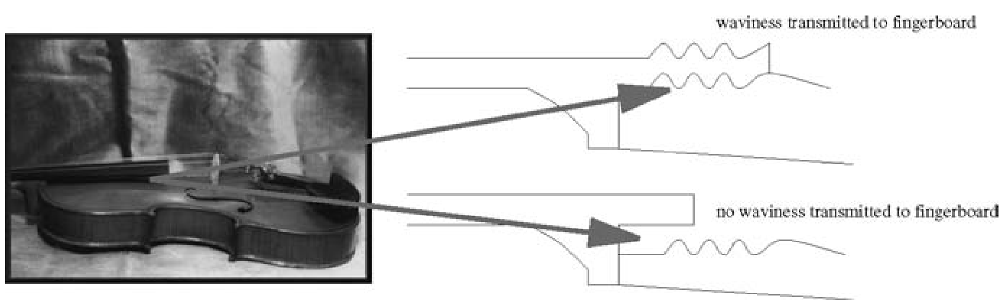

Figure 6. An illustration of the principle of avoiding unnecessary mechanical coupling.

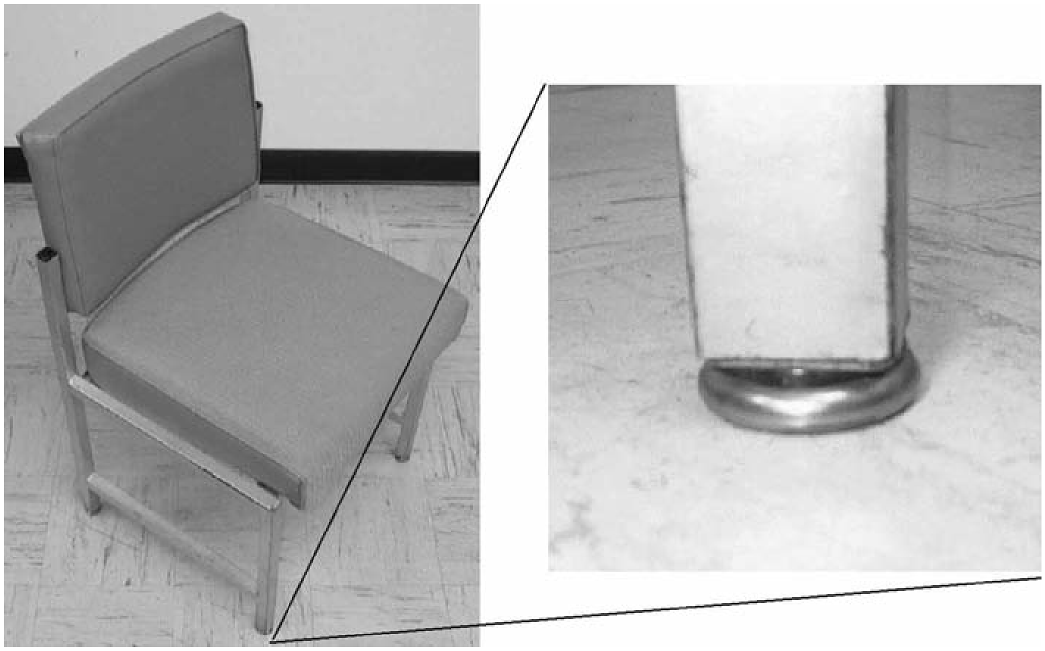

Figure 7. An illustration of the principle choosing elastic components for tight fits.

design for manufacturing are an entire research field—one fuelled by its practical dividends in production and manufacturing. Many of the principles of design for manufacture are good tolerance design principles. No comprehensive review of design for manufacturing is presented here. Instead, the focus is on new design for manufacturing principles with a clear impact on tolerance design. The principles here are those that pay high consideration to the manufacturing process during embodiment design.

2.3.1. Cut mating forms from the same part stock: the sandwich principle. If two or more parts have features that need to align, manufacture these features first then cut the component. This approach allows the errors, whatever they are, to be the same (in cross-section) for mating surfaces. A sandwich provides a clear analogous example. Two pieces of bread, if adjacent in the original loaf, make a sandwich with minimal filling leakage. Whereas, a piece from the middle and a piece from the end will leak filling everywhere unless the loaf is toleranced tightly. An graphical illustration this principle is included later in figure 16 (section 4).

2.3.2. Design to existing errors: the door gap principle. If an existing component or system has a performance measure that is out of tolerance, use that performance parameter's value as the reference for additional design. Designing to existing errors is often more important than correctness. A perfectly square door in a skew door frame will look worse (the gaps) than a door that is cut to fit the error in the door frame. This principle is illustrated in figure 8. Another way to think of this principle is to design to localized coordinate frames.

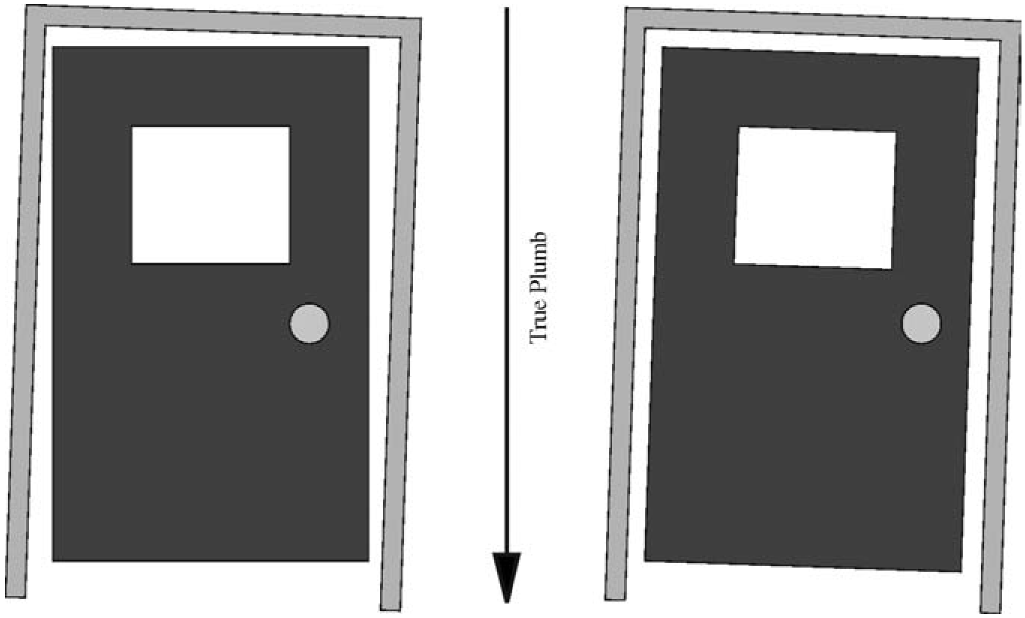

Figure 8. An illustration of principle of designing to existing errors.

3. Formalizing and classifying the principles

In this section, a formalization for organization of the principles is presented. The goal here is to provide some structure so the principles may be better understood and thus more easily used. For example, when does one use one principle and not another? Or, at a certain stage in a design, what principles are still viable for application?

The principles are classified in a way to make them distinct: in what way is each principle the same and in what way is it different. Because these principles are different in different ways, the classifications categories are not equivalent. For example, an off-line and on-line classification indicates 'when' a principle is applied, whereas the change classification indicates 'to what' the principle is applied. Table 1 summarizes the principle classifications. Before moving on to the problem of adding new principles, some clarification of the classes is in order.

Off-line principles are applied at the design stage. On-line principles are applied anytime after this stage, including manufacturing and during use. The 'add a feed forward' tuning parameter principle is an off-line principle. The addition of a feedback tuning parameter affects both off-line design and also control performance during use: it is on-line.

Another characteristic that distinguishes between the principles is the level of detail that they change the design. Does the application of the principle result in a change in product functionality, architecture, solution principle, parameter values, or manufacturing process? For example, the 'add feed forward tuning parameters' principle adds a positioning function to the product. Similarly, the principle 'add feed back tuning parameters' adds the functions of 'sense', 'measure', and 'change' to the product functionality. The principle of 'use elastic components for tight fits' increases the functionality of the device. This principle implies the addition of an 'allow a degree of freedom' function to the product that was not originally included in design. The principle of 'preload elements to prevent free play' adds a 'change force' function to the product.

Principle	Class								
	On-line	Off-line	Single calibration	Continuous calibration	Automatic calibration	Functional change	Architectural change	Form change	Parameter change
Add adjustment, or feed forward tuning, parameters	✓	✓	✓			✓			
Add feedback tuning parameters	✓	✓			✓	✓			
Preload elements to prevent free play		✓	✓			✓			
Distribute tolerance stack ups	✓	✓					✓		
Reduce the number of part and module interfaces							✓	✓	
Use analogue adjustments	✓	✓		✓		✓			
Use the minimum number of constraints		✓					✓	✓	
Move the nominal set points		✓	✓						✓
Choose elastic components for tight fits				✓		✓			
Cut mating features from the same part stock	✓	✓	✓						
Design to existing errors		✓	✓						✓

Table 1. A classification of the tolerance design principles.

The principle 'use the minimum number of constraints' implies a change in the solution principle or form of the solution. The application of these principles will not affect the functionality of the product. This classification is distinct from the parameter change because it does not imply a change in the value of parameters; it suggests a change in the structure of the solution.

The principles in the classification of architectural change are those that imply a change in layout and position of components, without a change in functionality. The principle of 'distribute tolerance stack ups' falls into this category.

The classification of manufacturing change is for those principles that imply a change in the way a product or components is (are) manufactured, but not in parameter values, solution principle, or functionality. Note that the principle of 'distribute tolerance stack ups' is classified as both a manufacturing change and architecture change principle. This principle can be applied to review a manufacturing process or the layout of modules and components in a product.

The tolerance design principle of 'move the nominal set points' does not change the functionality of the product. The application of this principle does not result in the removal or addition of any or all design parameters. On the other hand, this principle allows for a change in all the design parameters. As an alternative example, the principle 'design to existing errors' assumes some existing parameter values to be fixed. In this sense, the principle of 'design to existing errors' is a compensating principle—it changes the system to counteract for existing errors.

The classifications of single, continuous, and automatic calibration are a combination of when and how the principle is applied. The single calibration is a one-time adjustment. It is most useful for compensating for errors resulting from manufacturing variability. Continuous calibration implies a modification of the design that allows it to be adjusted to handle variability both during and after manufacturing. An example of a design modification resulting from the application of this principle is the adjustment on a crescent wrench. Automatic calibration is similar to the continuous calibration in that it adjusts to handle noise continuously, but it implies a modification in the design to handle the adjustment without user input.

3.1. Adding new principles

A formalization for the organization of the tolerance design principles has been provided. Although the principles presented here are general and broad in impact, it is unlikely that this list of principles is comprehensive: there may be other principles useful for tolerance design. Thus, a framework for developing and integrating new tolerance design principles into the aforementioned formalization is presented here.

A review of the tolerance principle classification in Table 1 reveals a uniqueness constraint on principles. No two principles exist in the exact same set of classes. If two principles do exist in the same set of classifications, these principles are, in practices the same. Similarly, no principle exists in each classification. A tolerance design principle that exists in each classification is too general and requires further decomposition.

When adding a new principle, a possible event is the need to add a new classification. If this is the result, a new classification has requirements essentially equivalent to the requirements already discussed for adding a new principle. For example, all the existing principles must not exist in this new candidate classification. Similarly, a new classification may not contain the exact set of principles as an existing classification.

4. Design example: a guitar pickup winder

The tolerance design principles are shown here as applied to an example design problem. The goal is to show how, through application of the principles, a crudely constructed prototype can achieve high-precision performance.

The example problem is the design of an electric guitar pickup winder. The term pickup refers to the electromechanical transducer that transforms the motion of the guitar string into an electric current. The current is then amplified and transformed into sound. The development of magnetic pickups for use in guitars begin about 1931 and became common place in the late 1950s (Brosnac 1983). A standard pickup with cover removed is shown in figure 9. Figure 10 shows the same pickup before the addition of the wire coil. The coil winding consists of 6000–12 000 turns of small, insulated copper wire. This wire is generally 41, 42, or 43 gauge.

A brief visualization of a machine or process that winds this wire neatly (the wire diameter is 58–83 µm) without breaking it (the maximum working strength is varies from roughly 0.5 N to 1 N) indicates a potential need for precision. Thus, the appeal of this problem for a tolerance design case study.

There are two types of pickup winders in common use currently. One is a larger industrial machine designed to wind hundreds of pickups a day. These winders are largely automated and use computer-regulated feedback control or careful synchronization and precision machinery to ensure an even wind. The other type of pickup winder popularly in use are essentially nothing more than a sewing machine motor to which the bobbin is attached. The wire is guided onto the bobbin by running the magnet wire through the operators hands or fingers.

The industrial-style pickup winders have the advantage of being able to wind many pickups accurately, although to some this accuracy is a disadvantage [3]. The sewing machine pickup winders have the advantage of lower initial cost and vintage mystique. These winders, however, have the disadvantage of a less accurate and neat wind, as well as requiring a certain amount of expertise on the part of the operator to prevent wire breakage.

The winder design of interest here is one that targets a distinct niche in the pickup winder market. The target customers for this winder are the guitar repair technician, custom luthier, and guitar tinkering hobbyist. In general, this winder will be used to repair broken pickups, wind custom designed 'one-off' pickups for custom guitars, and wind prototype pickups to test new pickup designs. This customer segment cannot

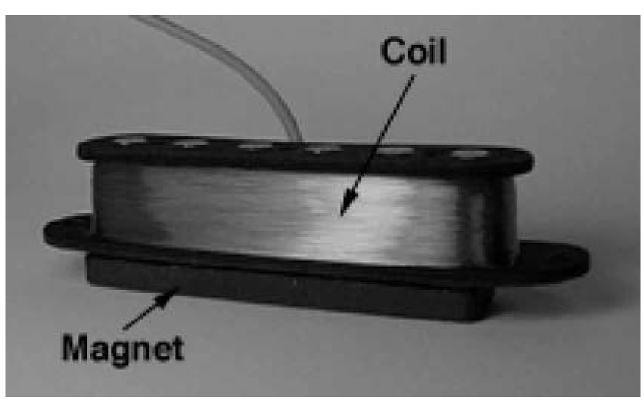

Figure 9. A pickup.

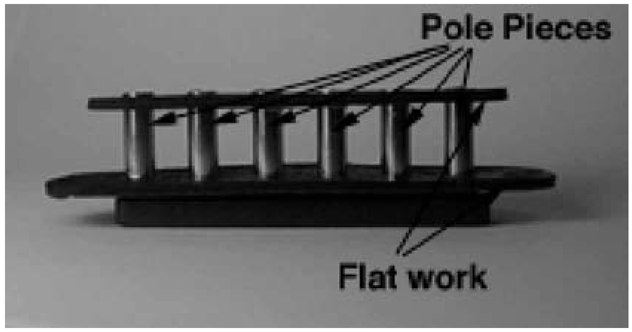

Figure 10. The pickup without the wire coil: the bobbin.

afford a computer-controlled winder. The sewing machine winder is not an acceptable option either. First, this customer group does not want to develop the necessary expertise to wind pickups on the sewing machine motor winder. Also, to wind specific prototype and custom pickups, the winder needs to be capable of producing both an accurate and inaccurate or 'vintage' wind. Thus, the need for an inexpensive, simple to use winder that can produce both an accurate and vintage style coil on most common guitar pickups (or bobbins). Such a winder is the design presented here.

An initial design concept that includes general layout, architecture, and operational principles for the winder is shown in figure 11. The magnet wire spool is held in a simple stand. As the wire is pulled off the spool, it runs through the tensioner. The tensioner works by running the wire between two pieces of wool felt. The felt is squeezed between the tension clamp and the shuttle base by two screws. Thus, the wire is squeezed between the felt pads providing a drag force and tensioning the wire.

The tensioned wire moves past a rotating guide wheel on the wire guide shuttle. To move the position of the wire and feed it correctly onto the bobbin, the wire guide shuttle moves back and forth in the shuttle track. The user inputs this motion by

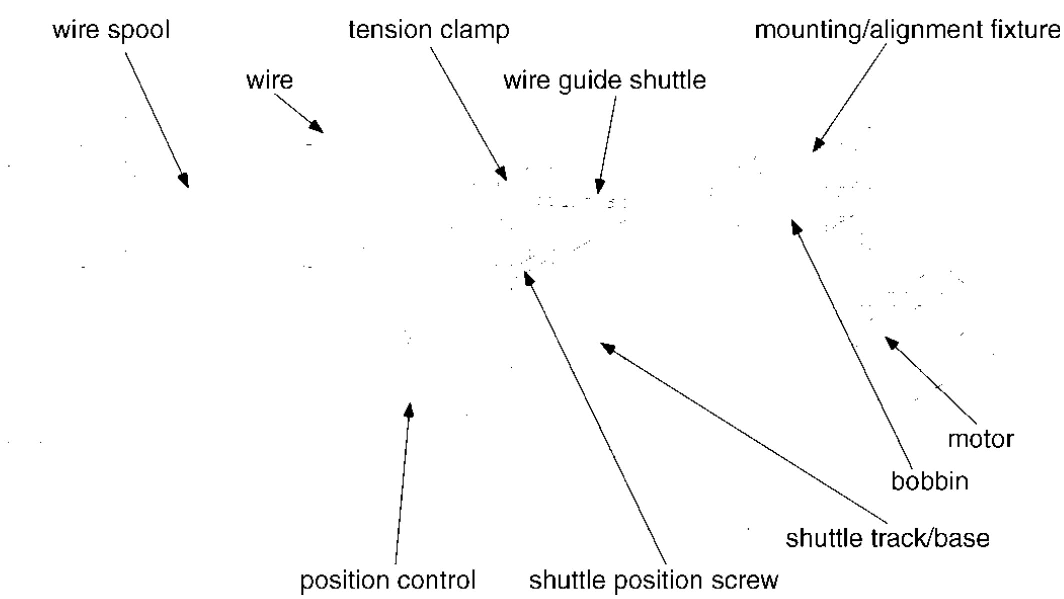

Figure 11. The pickup winder concept.

rotating the position control and thus the shuttle position screw. The bobbin is attached to a rotating shaft via a mounting fixture. The motive force for the bobbin rotation is a small electric motor. The motor control electronics are not shown in figure 11. In the following sections, procedures and principles of tolerance design will be developed and applied to this winder concept.

4.1. Application of the tolerance design principles

In this section, the tolerance design principles, as they are applied to the proposed pickup winder design, are discussed. The application and presentation is discursive, as that is how the principles are applied in this example. In other words, during the concept generation and evaluation process, the principles are reviewed to see if they can be incorporated to improve the tolerance design. In general, a structured methodology and theoretical base for the application of most of these design principles remains future work. Exceptions include moving the nominal set points and adding adjustment, or feed forward tuning, parameters (Taguchi 1986, McAdams and Wood 2000).

To ensure precise positional control of the magnet wire, the bobbin must rotate in a plane. Also, this plane must be perpendicular to the direction of wire feed from the wire guide wheel. If this condition is not met, the axis of coil is not coincident with the axis of the bobbin, thus resulting in a coil as shown in figure 12. These two conditions depend on a number of geometric constraints on the perpendicularity of the direction of the shuttle travel and the perpendicularity of the bobbin with the shaft. Depending on the method of construction, the manufacturing process may or may not provide the tolerance required for this perpendicularity condition.

Ensuring that the bobbin is perpendicular to the axis of rotation is a challenging design and manufacturing problem. The approach here is to use the tolerance design principles to remove it all together. We rely on one of the system-level tolerance design principles for a solution. The solution to this is the inclusion of the alignment degree of

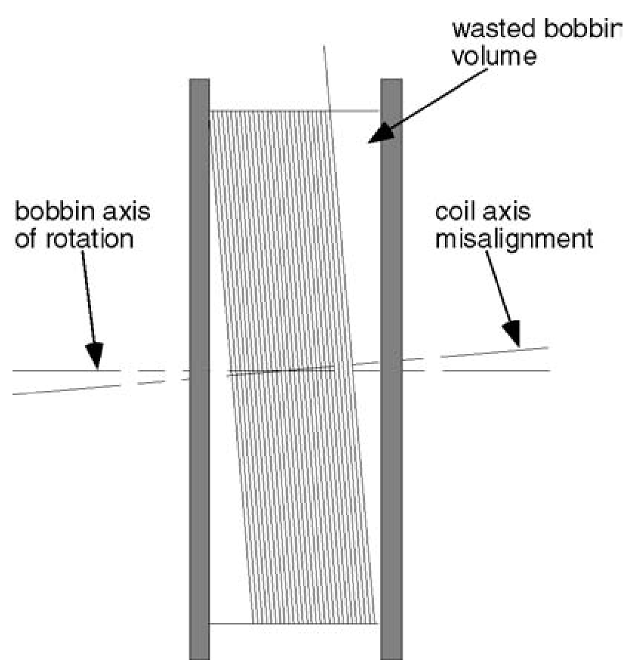

Figure 12. The error in the coil resulting from bobbin misalignment.

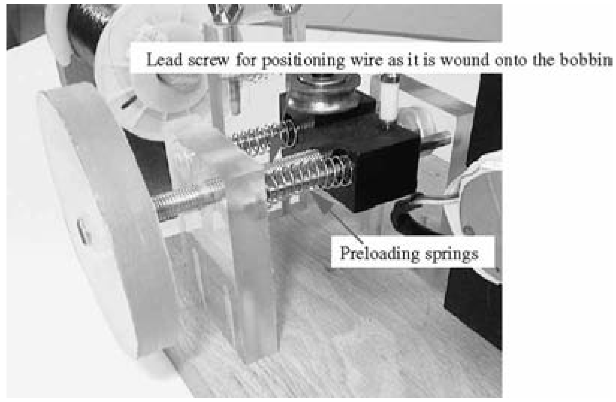

Figure 13. The design principle of using analogue adjustments to enable precise positioning of the wire as it is wound onto the bobbin. Also illustrated is the principle of pre-loading elements to prevent free play.

freedom in the bobbin mounting plate as shown in figure 11. This is an implementation of the wheel alignment principle: rather than try to enforce impossible to achieve tolerances, add a continuously adjustable tuning parameter.

Another implementation of the usage of analogue adjustments is the lead screw used to move the wire control shuttle back and forth (figure 13). Through this solution, the guide wire wheel can be positioned anywhere along the length of the threaded rod. Using analogue adjustment in this way prevents tolerance requirements of the order 0.03 mm that would be required for some type of discrete back and forth motion.

To develop an even and graduated coil on the bobbin, the position of the wire needs to be user controllable within less than one diameter of the wire (see figure 14). Based on the proposed solution concept, an important tolerance-dependent performance aspect of this system is stack up of the male and female thread variations in the position screw-guide shuttle system. As the shuttle reverses direction to move the wire back and forth across the bobbin, the stack up of the variational error in the position screw–guide shuttle system allows a small backlash during a change in direction. This backlash induces difficulties in controlling the position of the wire as it is guided onto the bobbin.

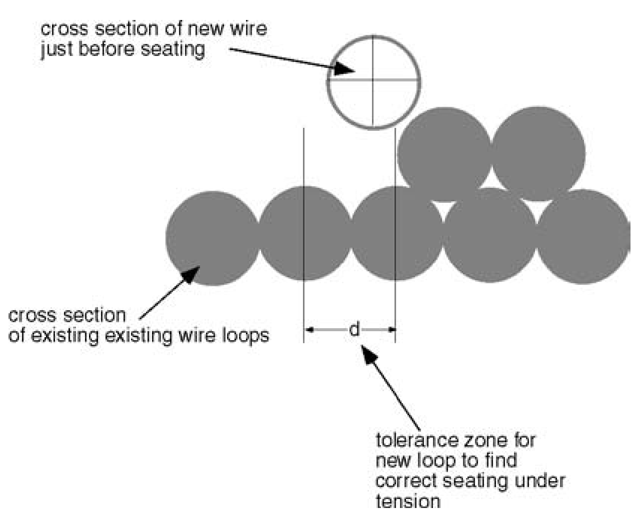

Figure 14. The position control precision need of the guide wheel.

To keep the design simple as well as inexpensive, it is advantageous to use an off-the-shelf threaded rod for the lead screw. Using standard parts and dimensions has advantages both in cost and maintenance for large-scale manufacturing problems. Thus, it is advantages to avoid a precision tolerance specification on the lead screw.

A precision tolerance requirement for the lead screw is avoided through application of the bicycle spoke principle. If the guide shuttle can be loaded so as to continually push to one side of the power screw-guide shuttle interface, there will be no backlash. Shown in figure 13, a spring is added between the position control wheel support and the wire guide shuttle coaxially with the power screw. This spring keeps a load on the shuttle, thus preventing backlash.

Continued inspection of concept shows another potential tolerance problem preventing an even and graduated distribution of wire on the bobbin. Shown in figure 15 is a side view of the shuttle and bobbin mounting assemblies with the bobbin in place. From figure 15 it can be seen that as l grows small, the lip of the guide wheel will interfere with the wire. Interference will cause small shock load in the wire and thus misalignments and other noise in the coil. Analysing this problem with the parameter tolerance design theories leads to a solution to the problem. Using Taguchi's robust design principle, the nominal set point for the length l can be increased until the natural tolerance on l does not cause interference with the guide wheel lip.

Next, the use of the sandwich principle removes an assembly tolerance problem from the design. Two screws are used to squeeze blocks together, causing the friction and thus tension in the magnet wire. The positions of the screw holes in the two

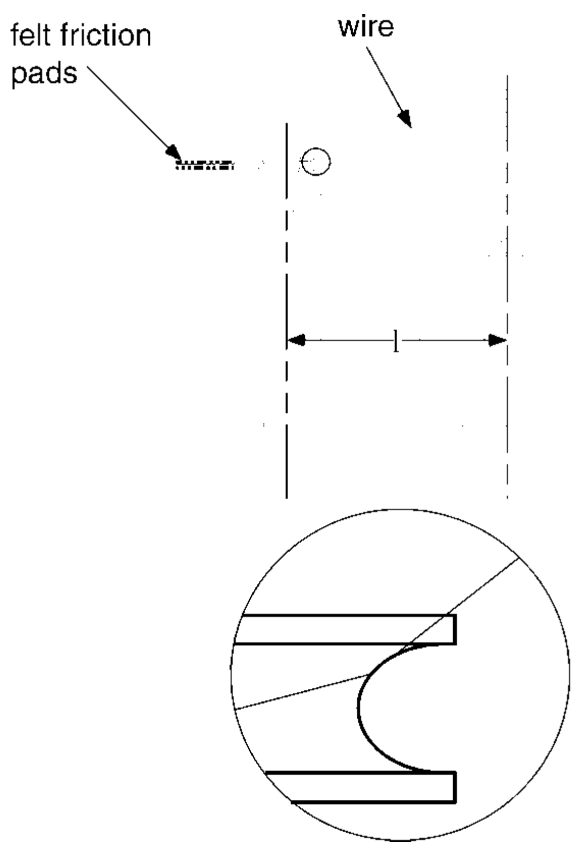

Figure 15. A schematic of the guide wheel interference problem.

blocks, the diameters of these holes, the diameters of the screws, and thread variations results in a classic geometric tolerance stack-up assembly problem (figure 16).

The use of the sandwich principle eradicates the tolerance specification requirement. If the parts are cut from the same stock after drilling and tapping the threads, the positional variations in the two holes are removed.

5. Insights, extensions, and summary

In the present article, novel principles for tolerance design are presented. These principles are formally organized to facilitate usage and extension. The usage and impact of these principles is shown through an example application to an original design problem. The design case study is an electric guitar pickup winder.

These principles have a significant impact on both practice and research in tolerance design. A key design insight of the research presented here is that tolerance design extends beyond assembly requirements and parameter design. Tolerance issues can be addressed through changes in product architecture and functionality. Using these principles, a practicing designer now has the ability to synthesize, evaluate, and improve the tolerance design of a product at the earliest stages of design. The precise and quantitative nature of tolerance design can now be approached early in the design stage with qualitative principles.

As an impact on tolerance design research, these principles provide a focus for developing new methodologies that will have a high impact on engineering practice. Each principle can be extended beyond the qualitative to a complete and quantitative theory. The principle of moving the nominal set points (Taguchi's robust design) has a wide body of existing theory and practical case studies that enable many different applications, both quantitative and qualitative. The principle of adding adjustment,

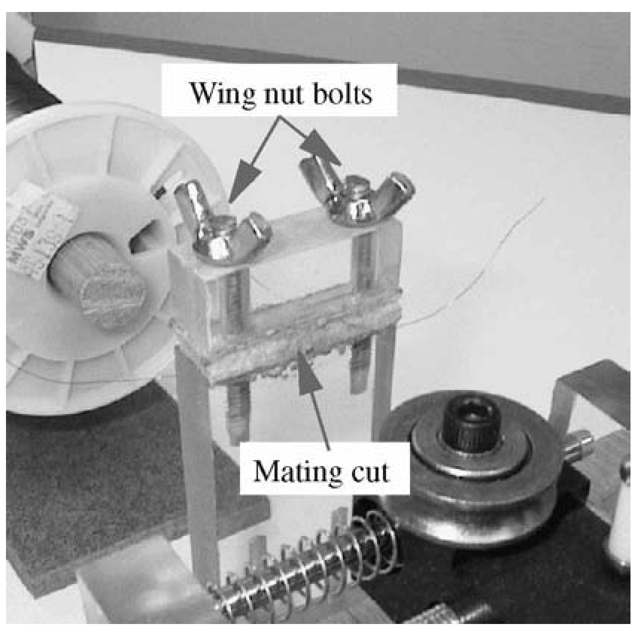

Figure 16. The design principle of cut mating forms from the same part stock. The holes for the bolts are drilled first. Then, the mating stock is cut into two pieces.

or feed forward tuning, parameters has also been developed beyond the qualitative to the quantitative. The tuning parameter tolerance design principle has been extended to include a complete step-by-step methodology and quantified techniques for finding a best parameter for tuning and setting the ranges on tunability (McAdams and Wood 2000).

NOTES

1. This is accurate given the specified testing procedure.
2. Followed by formation of a hypothesis and the test of the hypothesis.
3. What constitutes the 'best' winding for a pickups is surrounded by much folklore and personal bias.

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