Additional Information - Computer Modeling
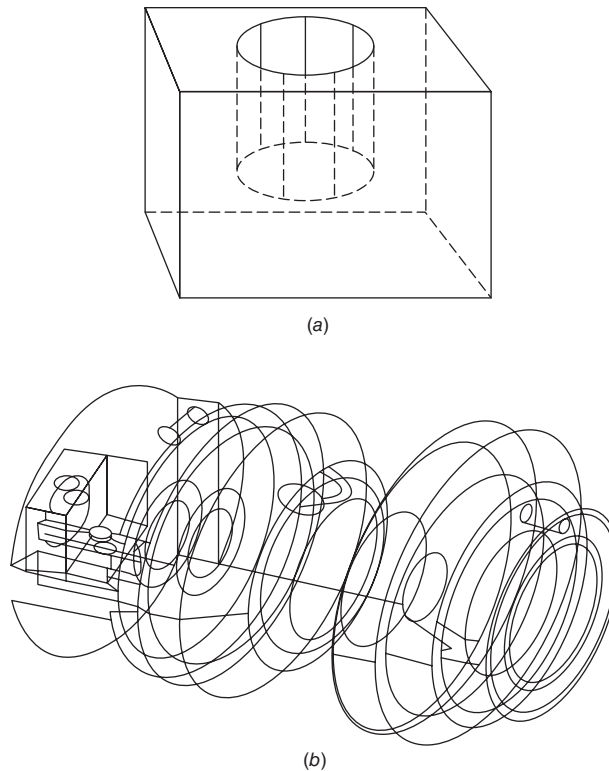

(a)

(b)

FIGURE 1
Examples of wireframe models.

A Brief Look at the Evolution of Digital Solid Models

A solid modeling system must unambiguously describe the three-dimensional shape of the object.[1] It must be able to distinguish between the inside and the outside of the object, and be able to support the calculation of mass properties such as weight and moment of inertia. In a two-dimensional CAD drawing the object is created by drawing lines, arcs, circles, and other forms on a plane in the manner of an electronic drafting board. The three-dimensional shape is conveyed with orthographic projections. This is only a little better in delivering information than a conventional hand-drawn portrayal. The advantages of a 2-D CAD drawing are the ability to make easy drawing modifications, the ability to use predrawn modules, and the fact that there is much more precision in dimensions than with a drawing made by hand.

1. J. MacKrell, "Computer-Aided Design," *ASM Handbook,* vol. 20, *Materials Selection and Design,* ASM International, Materials Park, OH, 1997, pp. 155–65; D. LaCourse (ed.), *Handbook of Solid Modeling,* McGraw-Hill, 1995; P.K. Wright, *21st Century Manufacturing*, Prentice Hall, Upper Saddle River, NJ, 2001; T.C. Chang, R.A. Wysk, and H.P. Wang, *Computer-Aided Manufacturing*, 3d ed., Pearson Prentice Hall, Upper Saddle River, NJ, 2005.

A three-dimensional *wireframe model* adds little additional information, Fig.1. The surfaces between the wireframe edges are not defined, and the computer is unable to determine what is inside or outside of the object being drawn. Wireframe models often are confusing and difficult to interpret because of extraneous lines, Fig. 1*b*.

The next evolution in computer modeling was to define the surfaces between the edges of the wireframe model. With such a surface model the definition of the object is more complete, and the model can be used with finite element analysis and numerical-controlled (NC) machining programs. Color-shaded images (renderings) may be created. [2]

Methods of Generating Solids

Current practice offers choices in the way that solid models are represented. Solid models provide information about what is inside the 3-D model as well as information about the surface of the object. The two basic techniques of solid modeling are *constructive solid geometry* (CSG) and *boundary representation* (B-rep), Fig. 2. With CSG the solid is constructed in building-block fashion by combining primitive shapes like a cube, cylinder, cone, or sphere. These primitives may be scaled, rotated, and translated in space. They are then combined using the Boolean operations of union, difference, and intersection (Fig.3). The union operation (a) combines the two primitive shapes. The shape resulting from a difference operation resembles the original shape with the area of overlap removed. Note that a difference operation is sensitive to the order of operation. A-B gives a different shape (b) than B-A, Fig. 3*c*. With the intersection operation (d) only the volume of overlap remains.

In a boundary model (B-rep), solids are represented by the sets of faces that enclose them completely. To ensure that the boundary model is topologically valid, it must satisfy the Euler-Poincaré relationship between the number of faces (F), edges (E), vertices (V), inner loops of faces (L), bodies (B), and through holes (C).

$$F - E + V - L = 2(B - C) \qquad (1)$$

In the B-rep model, the geometry is created and the topological validity is checked at the same time. The database must store information about the connectivity of the faces and the equations defining the geometry of the faces. A B-rep model is useful for complex parts that cannot be modeled conveniently with primitive shapes. It defines the part topology and geometry separately. After the topology has been defined, many different operations can be performed to adjust the geometry without changing the basic topology. A major disadvantage of B-rep modeling is that it is difficult to guarantee closure.

Sweeping is the creation of a solid shape by moving a line or a plane along a defined trajectory (Fig. 4). When the trajectory is a straight line, the resulting shape is made as if by an extrusion operation, as shown in Fig.4. The sweeping method is fast and easy to use.

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2. J. D. Foley, A. Van Dam, S. K. Fenner, and J. F. Hughes, *Computer Graphics: Principles and Practice,* 2d ed., Addison-Wesley, Boston, 1990.
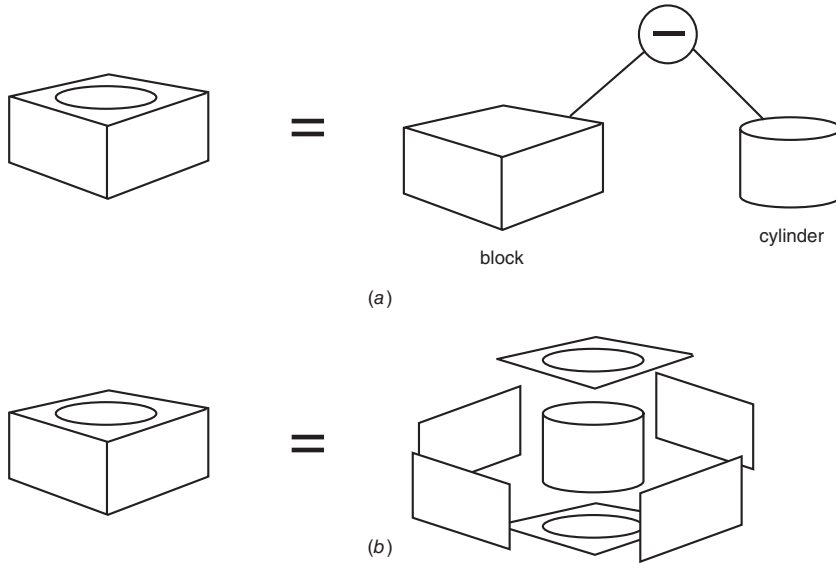
FIGURE 2
Two basic methods for representing solids in CAD: (a) constructive solid geometry (CSG);
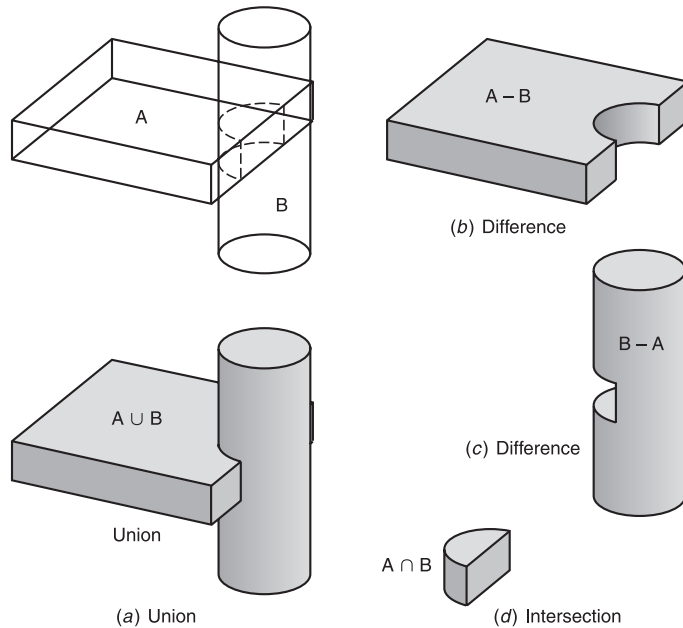(b) boundary representation (B-rep).

FIGURE 3
Three Boolean operations involving primitive shapes A and B: (a) union; (b) difference A-B;
(c) difference B-A; (d) intersection.

① A two-dimensional lamina is created with straight-line elements and arcs to represent the basic outline of the part base.

② A solid object is created by applying the linear sweep operator on the lamina.
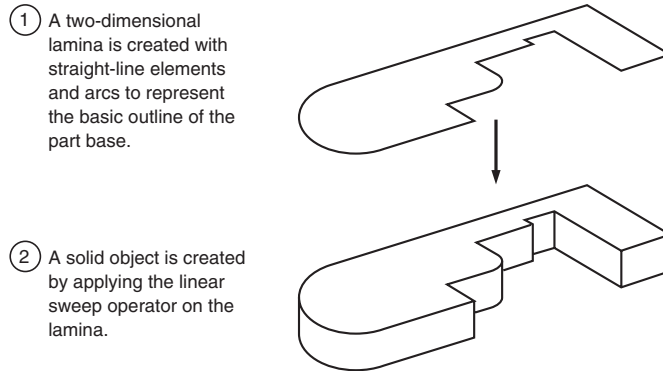
FIGURE 4
Development of a solid model by sweeping.

Spatial enumeration and cell decomposition use combinations of cubes to approximate solid shapes. They are organized as three-dimensional binary trees called *octrees*. Since modeling irregular surfaces requires almost an infinite number of tiny cubes, the method is very memory-intensive. Nevertheless, the method is very good at modeling irregular solids. In the variation called cell decomposition the cell may be a distinctive shape, like a finite-element mesh.

Both types of modeling, CSG and B-rep, have their advantages. The CSG representation is easier to edit because changes to the way primitives are used produce major changes with minimal input. However, the B-rep data structure deals with the details like edges and faces that the designer will want to change, so it is more amenable to an interactive environment. Since no one method of solid modeling has a clear advantage, most solid modeling software contains a hybrid modeler that provides for conversion between the two systems as needed.

Constraint-Based Modelers

Constraint-based solid modelers represent the current generation of CAD. They employ the methods of generating solids described previously with important embellishments. Constraints are used to create a set of rules that control how changes can be made to a group of geometric elements such as lines or form features. The types of constraints in common use are classified as numeric, geometric, algebraic, or attributes. Numeric constraints provide the position of points, the length of lines, angular values, etc. Geometric constraints provide for parallelism, perpendicularity, tangency, etc. Algebraic constraints combine numeric and geometric constraints into simple equations (diameter of B = one-half the length of A) or complex sets of equations that include inequalities and IF-THEN-ELSE branches. Attribute constraints define characteristics of the part such as color, material, surface finish, maximum stress, etc.

There are two types of constraint modelers in general use: *parametric* and *variational*. The difference between them has to do with how the constraint equations

are defined and solved. In a *parametric modeler,* all of the constraint equations are captured and solved in the order in which they are created. For example, if points *A* and *B* are defined as to location, and point *C* is defined as the midpoint between *A* and *B*, then the constraint equations for the system are $A =$ point($x1$, $y1$, $z1$); $B =$ point($x2$, $y2$, $z2$); $C = (A - B)/2$. In a parametric modeler points *A* and *B* can be moved and point *C* will automatically follow. In a *variational modeler* the set of equations is solved simultaneously so that the ordering of the equations is not so important. In the preceding example, points *A* and *C* can be moved and point *B* will automatically follow.

With a constraint modeler, if a fillet is placed between a plane surface and a cylinder, the fillet radius will change if the cylinder diameter changes. In a traditional solid modeler the fillet would not change, and the designer would have to remember to make this adjustment. In a constraint-based modeler the designer can countersink all of the holes in a part with a single command, rather than finding and changing every one. Parametric modelers impose order dependence, but they are faster than variational modelers. Most parametric modelers allow the user to redefine the parameterization and to reorder the parametric equations to allow different parameters to control the design. Variational modelers require more computing power to handle the more complex mathematics. However, they have the advantage that the designer does not have to give a lot of forethought to the hierarchy of the design constraints and can freely change the design without being limited by the order in which constraints were defined and features were added.

Constraint-based CAD systems combine constraints with form features. Features are higher-level constructs than lines, curves, and surfaces. Features such as slots, through holes, and blind holes are predefined and can be called up with a few commands rather than having to be created each time with Boolean operations. Features combine geometry with a set of dimensions and knowledge of how the feature combines with the solid object to which it is applied, that is, the design intent. They save the designer time because, since they are defined parametrically, the drawing can be quickly updated just by changing a dimension.

Constraint modelers also are relational modelers. Figure 5 shows a block with two features, a slot and a pair of holes. The slot is constrained by a relation, $d_2 = 0.6\, d_1$, such that whatever the value of d_1 the slot will always be 6/10 of the distance
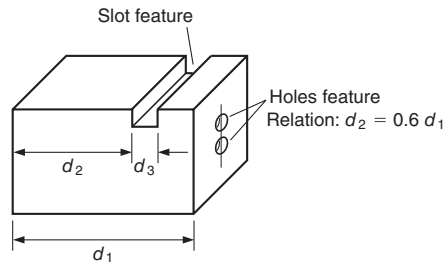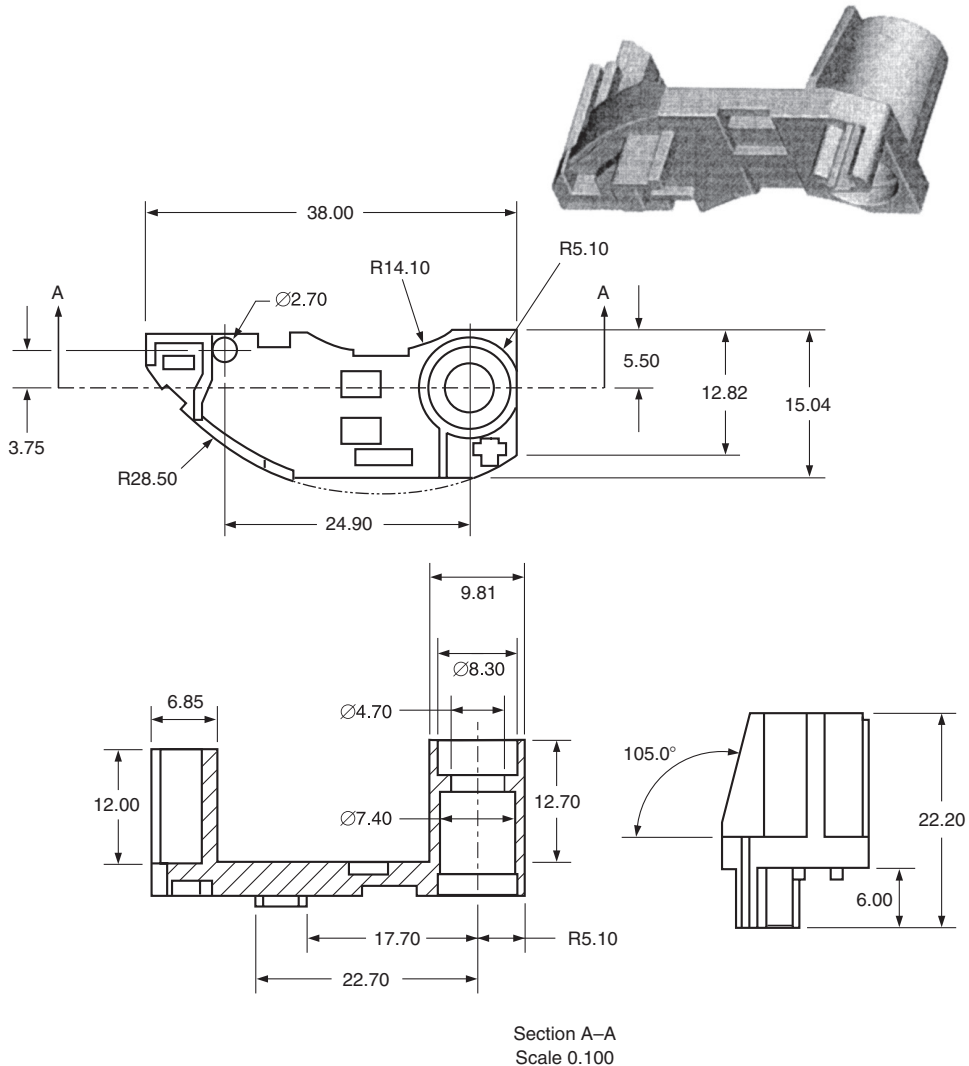

FIGURE 5
A part with two features: a slot and two holes.

FIGURE 6
Digital geometric model of a brush holder for an electric motor (upper right) and the 2-D engineering drawing derived from the model. (Courtesy of Professor Guangming Zhang, University of Maryland.)

from the reference surface. The designer captures this design intent with the relational model.

Solid modeling software provides several modes of operation. The part mode is used to make a 3-D model of a part. Standard "shop drawings" using orthographic projection can be prepared from the solid model using the drawing mode. Figure 6 shows a solid model of a holder for the brushes of an electric motor and the 2-D or-

thographic projection drawing derived from it. Solid models also can be used to create exploded assembly drawings using the assembly mode. An important capability is the ability to associate data between different modes. Thus, if a dimension is changed in the part mode, the software will automatically change the same dimension in the assembly and drawing modes.

Other capabilities of solid modeling software include the ability to make section views, detail views, perspective views, and surface rendered drawings, and animation of assemblies. Solid modeling CAD software can automatically generate complete meshes for finite element analysis (FEA), and these can be linked with the FEA software to perform design optimization.

Computer Visualization

The rapidly growing power and speed of the computer has greatly increased its use in carrying out simulations of all kinds. The goal is to substitute analytical simulation for physical tests on actual models and prototypes, with the objective of reducing design time and cost. Two major classes of computer simulations stand out in design. The first deals with rapidly occurring events in solids[3] and fluids[4]. The other concerns the fast-growing field of the simulation of interactive product design. These forms of simulation are so realistic, and bring the human viewer so much into the modeling world, that they are becoming known as computer visualization.

Dynamic Analysis

Figure 7 shows the computer simulation of the deformation of the bottom dome of an aluminum soda can after it strikes the ground. For the simulation the computer uses a dynamical FEA that combines the equations that describe the complicated interplay of mass, velocity, acceleration, pressure of the fluid, and mechanical behavior of the can material to calculate and display the distortion of the can at 1 ms intervals after impact. Prior to the use computer simulations, a conventional development approach was used in which experimental designs were fabricated and tested. Such a program would take six months to a year, whereas computer simulation took less than two weeks.

Computer simulation is evolving from a specialized analysis done with supercomputers to a more conventional engineering analysis done on a computer workstation or PC. Event simulation software that combines kinematic nonlinear simulation with nonlinear static and dynamic FEA provides a visual three-dimensional image of the part in the deformed state caused by a dynamical event. For example, the designer of a coffee pot could simulate dropping it from a certain height to a surface of specified hardness. The computer screen shows the trajectory and bounce of the pot, whether it shatters or dents, and the stress contours at any time during the impact or bounce. The computer simulation is in effect a prototype test.

3. J. E. Crosheck, " Mechanism Dynamics and Simulation, " *ASM Handbook*, vol. 20, *Materials Selection and Design,* ASM International, Materials Park, OH, 1997, pp. 166–75 .

4. P. J. O'Rourke, D. C. Haworth, and R. Ranganathan, " Computational Fluid Dynamics, " *ASM Handbook* vol. 20, *Materials Selection and Design*, ASM International, Materials Park, OH , 1997 ,
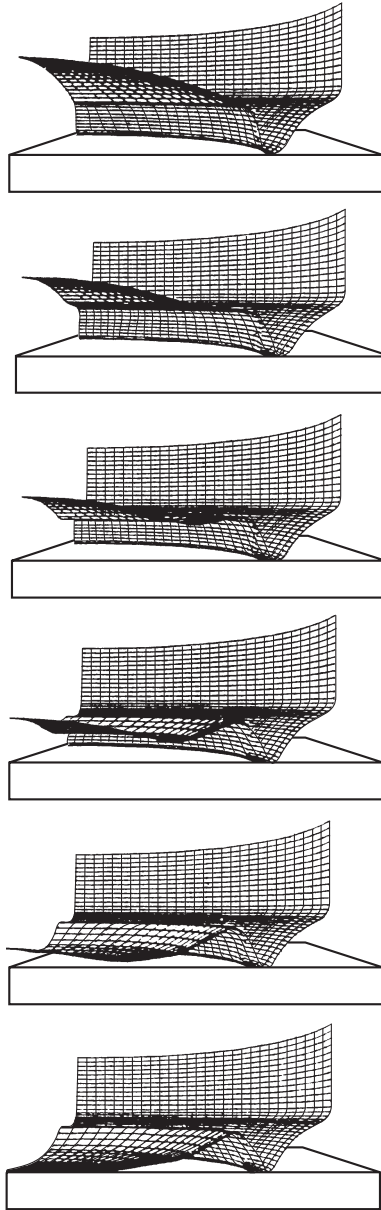
FIGURE 7
Computer simulation of bottom dome of aluminium can striking the ground. Only one-
quarter of the bottom of the can is included in the simulation. Note that the bottom dome
pops downward after the can hits the ground. (Courtesy of Alcoa.)

Virtual Reality (VR)

Virtual reality (VR) is the ultimate in computer visualization. VR allows the designer to interact with the computer-simulated environment as if he/she was actually present in the environment. Chiefly the interaction is visual, often with a stereoscopic headset to give depth perception. A head-mounted display automatically moves the viewing window in response to the user's orientation in VR space. Sound can be introduced with headphones and tactile sensing by using data gloves that allow the user to grab objects in the virtual space.

In design, virtual reality has its chief application in large, complex systems. In the design of a nuclear power plant, it has proved invaluable in determining the best step-by-step installation sequence for piping assemblies, valves, and other power plant equipment. For example, it can check out whether there is enough clearance between piping runs to allow a welder to make a defect-free weld. It can follow parts through a simulated manufacturing process in a "walk around mode" to determine bottlenecks and unanticipated delays. A major application for VR is in the training of military pilots (it is the ultimate video game) or soldiers for combat. It also can be used to train assembly operators or machine operators in complex operations.

It is possible to link computational tools, like FEA, with visualization. One application[5] involves the optimum design of shell structures that are subjected to vibration and noise radiation in an underwater environment. A FEA model for a shell structure loaded externally with hydrostatic pressure was used to find the optimum design of ring stiffeners, Fig. 8. The computation is made easier by breaking the FEA model of the shell structure into sections (substructuring) to reduce the degrees of freedom involved in modeling the dynamics of the coupled shell structure and surrounding fluid medium. Also, substructuring the system makes possible further reduction in computational resources by the use of parallel processing. The computations are converted to visual images and sounds of the modes of shell vibration that are viewed by the designer in a virtual reality environment. The designer can literally walk through the shell structure, adjusting parameters such as stiffener spacing, width, and depth, and observe the structure's response in terms of vibration mode shape, sound frequency, and maximum deflection. Because the designer is in the design loop as an integral part of the computer simulation, he or she can view and listen to the response of the shell structure in real time, and thereby gain considerable insight about the physics of the system that calculations alone would not provide. This is a great advantage in achieving an optimum stiffener design.

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5. W. Akl and A. Baz , " Efficient Virtual Reality of Quiet Underwater Shells ," *VirtualReality*, vol. 9, 2006, pp. 57–69 .
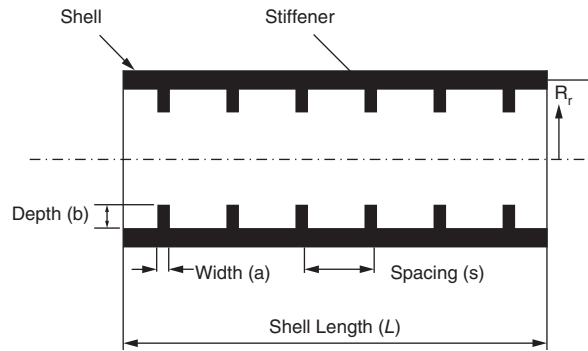
FIGURE 8
Schematic diagram of the shell structure.