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Attorney Docket No. 79491
Date: 22 January 2007

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Serial Number	11/489,812
Filing Date	17 July 2006
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20070206388

Attorney Docket No. 79491

METHOD FOR PARAMETRIC DESIGN OF THREE-DIMENSIONAL SHAPES

STATEMENT OF GOVERNMENT INTEREST

[0001] The invention described herein may be manufactured and used by or for the Government of the United States of America for governmental purposes without the payment of any royalties thereon or therefore.

BACKGROUND OF THE INVENTION

(1) Field of the Invention

[0002] The present invention relates to computer-aided design of three-dimensional shapes and more particularly, relates to a system and method for parametric design of three-dimensional hydrodynamic shapes.

(2) Description of the Prior Art

[0003] In designing and constructing vessels, such as surface and underwater vehicles, there is a general need for the design of fair, essentially free-form shapes. These shapes include, but are not limited to, propellor blades and hull surfaces such as submarine sails. These shapes are designed to obtain favorable performance in terms of speed, drag, fuel consumption, noise, vehicle maneuvering and seekeeping. Issues influencing the design of these shapes include performance, fabrication, and aesthetics.

[0004] A number of terms used herein to describe propellors and hull surfaces are defined as follows: Span is the radial direction outward from the hub of a propellor, along the length of the blade. Rake is a deflection forward or aftward from a radius of the hub. Chord at span is the longitudinal length of the propellor blade at a certain span or radius outward from the hub. Maximum thickness is the maximum circumferential thickness at a certain span. Thickness to chord ratio is the thickness to the chord at span. The root is the position where a propellor blade is joined to a hub. Camber is the curved deflection from the centerline of a chord given as maximum camber with a camber distribution. National Advisory Committee for Aeronautics (NACA) shapes are standard aerodynamic and hydrodynamic shapes having recorded properties.

[0005] Currently, computer-aided design (CAD) tools are used for developing shapes for surface or underwater -vehicles. In most cases, however, the ability of CAD tools to systematically evolve a series of free-form three-dimensional shapes is limited. Existing CAD tools are especially limited in regards to defining and designing a shape with parameters that are related to hydrodynamic and aerodynamic behavior. The design criteria for submarine sails, for example, include increasing enclosed volume, decreasing electromagnetic and hydroacoustic signatures, and maintaining the same drag and maneuvering performance as traditional designs. The existing CAD programs were not adequate in designing sail shapes and also were not able to relate the shape to hydrodynamic performance.

[0006] Specialized parametric blade geometry descriptions have been used for propeller design and analysis. The Generalized Propulsor Description (GPD), for example, was developed to address problems inherent in the design and description of propulsor blades for tactical scale vehicles (e.g., torpedo-size and smaller). GPD enables a propulsor to be designed parametrically in a global, three-dimensional manner where metrics (including pitch, rake, skew, chord, camber and thickness) are related to the hydrodynamic performance of the propulsor. A complete definition of these parametric functions for propellor blades is given in Ulman, J.S. and Krol, W.P., 1994, "Generalized Propulsor / Turbomachinery Description Standard: Introduction and User's Manual," NUWC-NPT Technical Document 10376 , 18 July, 1994, which is incorporated herein by reference.

[0007] FIG. 1 shows the blade geometry descriptions used in the prior art. A three dimensional coordinate system is given having a cylindrical stream surface 10 centered on the y-z axis. The radius of the stream surface is identified as R. The stream surface 10 extends along the x axis. A propeller 12 is shown intersecting the stream surface. The intersection of the propeller and the stream surface is given at 14. The propeller 12 has a blade mid-chord line shown as 16. A pitch line 18 extends from one extreme of the blade to the other along the stream surface. A camber line 20 is drawn along the midpoint of the thickness of the propeller. Thickness of the blade is given along the x dimension between a forward blade surface and aft blade surface. Camber is defined as the difference between the pitch line 18 and the camber line 20. A pitch angle φ is given as the angle between the pitch line 18 and a tangent to the stream surface 22.

[0008] These blade geometry descriptions usually are based on curves formed by the intersection of the three-dimensional propeller shape with cylinders coincident with the axis of rotation, referred to as stream surfaces. For cases where stream surfaces are essentially cylindrical, this basis allows for ready interpretation of the describing parameters. However, for other cases including those for many tactical-scale vehicles, this advantage is lost. Non-intuitive sections must be defined in way of the hub and the tip to account for the noncylindrical nature of the stream surfaces in these regions. To address these problems, the use of stream surfaces has been extended to include conical shapes, but these are still overly restrictive. Thus, the ability of GPD to design shapes that are not propulsors, such as submarine sails, is limited.

SUMMARY OF THE INVENTION

[0009] One object of the present invention is design and analyze three-dimensional shapes other than propellor shapes. Another object of the present invention is to extract parameters from any three-dimensional shape and relate those parameters with hydrodynamic performance.

[0010] In accordance with the present invention, a computer aided design method is used for designing three-dimensional shapes. The method comprises receiving an initial design file, which is a computerized representation of a three-dimensional shape. Parametric features are extracted from the initial design file. Extracting the features includes intersecting the three-dimensional shape with a plurality of intersecting surfaces, wherein the intersections form a family of intersection curves, determining span-wise distribution parameters for the family of intersection curves, and determining chord-wise distribution parameters for each of the intersection curves. At least some of the span-wise distribution parameters and the chord-wise distribution parameters are modified, and a new design is created for the three-dimensional shape using the modified span-wise distribution parameters and the chord-wise distribution parameters. The three-dimensional shape is preferably a hydrodynamic shape, such as a propeller shape or a shape of an underwater vehicle sail. The intersecting surfaces can include a plurality of axisymmetric surfaces or arbitrarily-oriented cut planes. The span-wise distribution parameters preferably include one or more of midchord pitch angle, rake, skew, chord length, maximum blade section camber, and maximum blade section thickness. The chord-wise distribution parameters preferably include thickness and/or camber. Modifying the parameters can include smoothing the parameters by applying polynomial curves or changing the volume or surface area of the shape.

[0011] According to one method, a computational fluid dynamic (CFD) analysis is performed on the new design. The steps are preferably performed iteratively until a final design is created. A final design file can then be output.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] These and other features and advantages of the present invention will be better understood in view of the following description of the invention taken together with the drawings wherein:

[0013] FIG. 1 is a diagram of the coordinates used for propeller design utilized in the prior art;

[0014] FIG. 2 is a schematic block diagram of a parametric design system, according to one embodiment of the present invention;

[0015] FIG. 3A is a flow chart illustrating a method of designing a three-dimensional shape, according to one embodiment of the present invention;

[0016] FIG. 3B is a flow chart illustrating a method of designing a three-dimensional shape, according to another embodiment of the present invention;

[0017] FIG. 4 is a graphical representation of a submarine sail shape intersected by axisymmetric stream surfaces, according to one example of the present invention;

[0018] FIG. 5 is a graph illustrating the stream surface distribution of the stream surfaces shown in FIG. 3 in the radial direction;

[0019] FIG. 6A-6D are graphical representation of submarine sail shapes intersected by arbitrarily-oriented cut planes; and

[0020] FIG. 7 illustrates the set of graphs produced by one of the set of cut planes of FIGS. 6A-6D.

DESCRIPTION OF THE PREFERRED EMBODIMENT

[0021] The parametric design system 24, FIG. 2, according to the present invention, is used to parametrically design and analyze three-dimensional shapes. According to the exemplary embodiment, the parametric design system 24 creates a parametric geometry description that defines three-dimensional shapes in a manner relevant to hydrodynamics and then modifies the parametric geometry description to improve hydrodynamic performance. According to the exemplary embodiments described herein, the three-dimensional shapes are rotating shapes such as propellers and translational shapes such as submarine sails. The present invention can also be used to design and analyze other three-dimensional shapes including, but not limited to, ship and submarine hulls, rudders, control vanes, sonar domes, towed arrays, unmanned underwater vehicles (UUVs), and torpedoes. The present invention can also be used to design and analyze aerodynamic shapes.

[0022] The parametric design system 24 is preferably implemented as software, hardware, or a combination thereof and includes a number of functional components. A feature extractor 26 extracts two-dimensional parametric functions or features from a three-dimensional shape. A geometry modifier 28 modifies the parametric functions of the three-dimensional shape, for example, using parameter/performance data 30 relating parameters to performance. A design generator 32 creates new designs of the three-dimensional shape using the modified parametric functions. In a preferred embodiment, a design analyzer 34 performs a mathematical performance analysis on the new design and preferably relates the parameters to performance to create parameter/performance data 30. The parametric design system 24 is preferably used with a computer-aided design (CAD) tool 36, such as any CAD software known to one of ordinary skill in the art, which creates the initial design of the three-dimensional shape.

[0023] According to one method of the present invention shown in FIG. 3A, an initial design of the three-dimensional shape is created, step 110. In the exemplary embodiment, the initial design is a crude shape of a submarine sail. The initial design can be created from a conceptual basis, for example, using pencil and paper sketches, CAD model shapes, non-uniform rational b-spline surfaces, other software models, and shapes based on canopy design work. The initial design is preferably converted to an initial design file, such as a CAD file, which is a computerized representation of the three-dimensional shape, step 112. In one embodiment of the present invention, the initial design CAD file is created using the CAD tool 36 (FIG. 1). The initial design file is input to the parametric design system 24, step 114, and a parametric geometry description is created for the three-dimensional shape, step 116.

[0024] To create the parametric geometry description, the initial design file is converted into appropriate points for extraction. The extraction process includes specifying intersections of the three-dimensional shape with a series of intersecting surfaces. These intersecting surfaces are usually selected based on hydrodynamic, structural, or geometric considerations, although any arbitrary surface can be used, as described in greater detail below.

[0025] The intersections of the intersecting surfaces with the three-dimensional shape form a family or series of two-dimensional intersection curves. The two-dimensional intersection curves are related to one another by generalized span-wise distributions. Each individual intersection curve is defined by generalized chord-wise distributions. Thus, a three-dimensional shape, such as a multiple-bladed propulsor or an underwater vehicle sail, is defined with three major components: intersecting surfaces, generalized span-wise distributions, and generalized chord-wise distributions.

[0026] According to one example of the parametric geometry description for a propellor blade, the intersecting surfaces preferably include axisymmetric surfaces or stream surfaces that usually correspond to the anticipated flow streamlines and are generally cylindrical or conical. They are generally oriented with the axis of rotation and modified where needed to conform to flow boundaries. Any number of stream surfaces may be used starting at the hub and finishing at the tip of the propellor blade. A normalized parametric value is assigned to each stream surface designating its span-wise position. Spacing between surfaces is arbitrary and may be concentrated in regions where geometry changes abruptly, for example, near root and tip. In one example, six span-wise distributions are used: mid-chord pitch angle, rake, skew, chord length, maximum blade section camber, and maximum blade section thickness. These functions are specified at each span-wise position. Also for each span-wise position, there is a pair of chord-wise or leading edge-to-trailing edge distributions: thickness and camber.

[0027] According to one example of the parametric geometry description for a submarine sail shape 38, FIG. 3, the intersecting surfaces are axisymmetric stream surfaces 40 having a cosine distribution (closely-spaced at inner and outer radii). The cosine distribution 44, FIG. 4, of the stream surfaces 40 gives good resolution since the distributions tend to change rapidly at the root and the tip and more slowly at mid-span. In this particular design, the generalized axisymmetric form of the stream surfaces is preferable because the forward portion of the sail shape 38 extends forward onto the curved nose. The innermost axis-symmetric stream surface 40A is preferably coincident with the submarine hull.

[0028] According to another example of the parametric geometry description for a submarine sail shape 38, FIGs. 6A, 6B, 6C and 6D, the intersecting surfaces are arbitrarily-oriented cut planes 46A-D having various distributions and orientations. The distributions and orientations include waterlines 46A, buttocks 46B, diagonals 46C, and meridionals 46D. As described above, the intersections form families of intersection curves 48 as shown in FIG. 7 that are related to one another through generalized span-wise distribution parameters. The intersection curves themselves are defined through generalized chord-wise distribution parameters.

[0029] The ability to use arbitrarily-oriented cut planes 46A-46D provides an advantage when designing submarine sails and other similar shapes. Propeller blades, although having complex three-dimensional shapes, look very two dimensional across the blade section cut. This characteristic produces a predominant local flow direction near the surface that traces around the blade section cut. In contrast, the desired sail shapes resemble arbitrary bulges having flows of greater three-dimensionality. These shapes often have a predominant local flow direction near the surface unlike the flow around the blade section cut. As a result, the distribution and orientation of the arbitrarily-oriented cut planes 46A-46D used to intersect submarine sail shapes and other similar three-dimensional shapes helps to correlate the shape to performance using parametric descriptions, as will be described in the example below.

[0030] The parametric geometry description including the two-dimensional parameters extracted from the three-dimensional shape is then modified by a user, step 118. Modifications include smoothing the span-wise and/or chord-wise distributions and any other modifications according to the desired criteria for the three-dimensional shape. The modified two-dimensional parameters are then used to create a new modified design of the three-dimensional shape, step 120. The performance of the new design is preferably analyzed, step 122, for example, using a computational fluid dynamic (CFD) analysis. Based on the results of this analysis, step 124, the design of the three-dimensional shape can be modified again or a final design CAD file can be created and output, step 126.

[0031] In addition to designing three-dimensional shapes, the present invention can also be used to generate parameters that can be related to performance, step 128, for example, as determined by the performance analysis. According to one example, the span-wise distributions and the chord-wise distributions extracted from a sail shape using cut planes (as shown in FIG. 6A) can be analyzed by calculating slopes and curvatures. Area and moment distributions under the chord-wise distribution curves 48 formed by the intersection with planes can also be related to performance.

[0032] Examples of correlating shapes with hydrodynamic and hydroacoustic performance are described below. Cavitation characteristics are related to leading edge radius and maximum thickness-to-chord ratio. Vortex formation is related to the ratio of maximum thickness to local chord for the outer half of the span. Drag is related to the slopes of front facing sides and to the slopes near the trailing end. Drag is also related to the projected section area versus axial location and the ratio of maximum projected section area over maximum projected buttock area.

[0033] FIG. 3B provides an alternative method of the current invention. According to this method, the user provides design parameter in step 140. These parameters include characteristics such as enclosed volume, maximum radius or height, maximum thickness or width, and specific envelope shapes. In step 142, the software selects a set of curves defining the shape that fit the user selected criteria. The user can then modify the geometry description in step 144 by including additional detail or specifying additional criteria. The additional detail may be physical characteristics such as greater detail concerning the enclosed volume or fillet radii. In step 146, the computer creates new geometry parameters from the modified geometry description. The new design is then subjected to analysis in step 148 to determine its fluid dynamic properties. Step 148 can be conducted by computational fluid dynamics. In step 150, the user determines if the new design satisfies the design criteria and is complete. Upon completion the computer outputs a new CAD design in step 152. If it is determined that the design requires additional work, the user is given another opportunity to modify the geometry description as in step 144. An optional step 154 can be conducted to relate specific parameters to performance. This can include relating hydrodynamic characteristics to parameters such as the smoothness of surface curve derivatives or fillet radii.

[0034] One example of modifying the design of a submarine sail shape using the system and method of the present invention is now described in greater detail. According to the design criteria for a sail of a submarine, the sail should have acceptable drag and hydrodynamic flow characteristics and should also contain a specified volume with specified dimensions. Also, the sail of a submarine should be doubly curved like a sphere or ellipsoid for avoiding radar reflection. According to this example, the extraction process using axisymmetric surfaces (as shown in FIG. 4) produces span-wise distributions that are not smooth and some that are highly irregular. A submarine sail surface can be made from a set of smooth curves that define the surface and yet have very erratic distribution parameters. Sails defined with smooth chord-wise and span-wise parameter distributions are likely to exhibit a shape that has smooth surface curves. Thus, the surface of the sail shape should preferably be parametrically smooth.

[0035] According to this exemplary method, the rough span-wise distributions are fitted with least-square polynomial curves (up to fifth order). These curve fits are then used to define modified span-wise distribution parameters, which form the modified definition of the three-dimensional shape. If necessary, the polynomial fits can be simplified or other-wise modified to obtain a more desirable shape. The parameters should preferably be as simple and change as little as possible while producing a shape that would meet the required criteria.

[0036] In this example, the symmetric nature of a basic sail shape results in skew, camber, and pitch distributions that are trivial for sail shapes. Hence these distributions are set to constants of 0, 0, and 90 respectively. From a hydrodynamic viewpoint, the span-wise and chord-wise distributions are preferably at least C^2-continuous (where C^n indicates a function with n continuous derivatives). Because the span-wise distributions were defined using the polynomials, these distribution curves are inherently C^∞-continuous. Although polynomials are used in one preferred embodiment, other types of fits can be used to smooth the distributions. The chord-wise distributions for each of the intersection surfaces in this example can also be modified. A chord-wise thickness distribution can be modified, for example, to provide more favorable hydrodynamic characteristics. Chord-wise distributions can also be modified to change the volume and/or the surface area of the sail shape.

[0037] According to one example, the initial design for the sail shape can be a NACA 66 (TMB modified) which is a NACA 66 section with a leading edge adjusted to improve cavitation performance, as described by Eckhart, M.K. and Morgan, W.B., 1955, "A Propellor Design Method, "Trans. SNAME, which is incorporated herein by reference. One objective of the new design developed from the chord-wise and span-wise distribution parameters of the NACA 66 shape is a sail having the same overall dimensions and shape of the initial design but with improved hydrodynamic smoothness and a rigorously defined shape.

[0038] The NACA 66 sail shape has a sharp trailing edge, whereas the modified sail design should have a blunt trailing edge. This is accomplished with a new chord-wise thickness distribution design. The chord-wise shape is redefined with a parabola for the leading edge radius of curvature, a parabola for the trailing edge radius of curvature, and a parabola for the difference of the desired chord distribution from the two parabolas. The superposition of these three curves constructs a section curve nearly identical to the NACA 66 (TMB modified) except with a rounded trailing edge and without the cusping of the rear portion of the curve. The new chord-wise thickness distribution is preferably non-dimensionalized to a chord of one and a maximum thickness of one. For example, the entire family of chord-wise distributions made up of ellipses would be represented by a circle having a diameter of one. The elliptical nature is produced by the maximum thickness to local chord span-wise distributions.

[0039] After the modified designs are obtained, computational fluid dynamic (CFD) analyses can be made to determine whether there is a need for additional design changes. The shape can then be modified again by manipulating the defining parameters, and/or altering the sail shape directly and smoothing it using parameters as described above. If wind tunnel experiments and further numerical simulations indicate a need for additional design changes to mitigate undesirable vortex effects, for example, the thickness-co-local chord distribution can be changed to resolve this difficulty.

[0040] According to another example, the parametric geometry description of a propellor blade can be modified in a manner similar to that described above for the sail design. One of the goals of the propulsor design is to examine the effect of leading and trailing edge sweep on generated noise. Skew and rake distributions can be found which minimize the reaction and resulting stresses at the blade roots and maximize leading and trailing edge sweep angles while fitting within axial extent constraints. If the second and higher order derivatives of the defined propellor surface are not smooth, the parametric geometry description of the surface can be modified to smooth out these derivatives.

[0041] Geometry for blades, fillets, and hubs may be exported directly to a stereo-lithography apparatus (SLA) rapid prototyping system without further post-processing. A generalized fillet design algorithm can be used to specify blade root and/or tip fillets. This fillet design algorithm allows complex, customizable fillets to be designed directly into the propulsor blade geometry. The inclusion of fillets into a propulsor blade design is often important to ensure structural integrity of the propulsor throughout its life cycle. The present fillet design algorithm is considered fully generalized and customizable for two reasons. Firstly, the designer has the ability to vary and control the fillet shape to any geometry that is preferred, not just circular. Secondly, in parallel with the variable shape, the magnitude or size of the fillet may be varied chord-wise around the base of the blade. Having full chord-wise control over the size and shape of the fillet allows one to optimize it and consequently extend the overload-bearing capability of the propulsor blade. The generalized fillet design algorithm has the ability to also define blade tip fillets independently, which is necessary for cases where a propulsor is designed having structural-support ring.

[0042] Accordingly, the parametric design system and method of the present invention can be used to design and analyze complex, free-form shapes, such as propulsor blades and advanced submarine sails. The parametric geometry description used in the present invention allows easy and systematic modifications to assist in design refinement. The ability to examine characteristics of various intersection curves enhances the correlation between shape and hydrodynamic and hydroacoustic performance.

[0043] In light of the above, it is therefore understood that within the scope of the appended claims, the invention may be practiced otherwise than as specifically described.

Attorney Docket No. 79491

METHOD FOR PARAMETRIC DESIGN OF THREE-DIMENSIONAL SHAPES

ABSTRACT OF THE DISCLOSURE

A parametric design system may be used to design, analyze, and manufacture articles having a three-dimensional shape, such as tactical-scale vehicle propulsor blades and advanced submarine sails. The system converts and initial design of a three-dimensional shape into parametric form, e.g., span-wise and chord-wise distributions, where features are more easily correlated with performance. As part of the design process, threes distributions may be systematically modified and converted back into standard forms for further analyses.

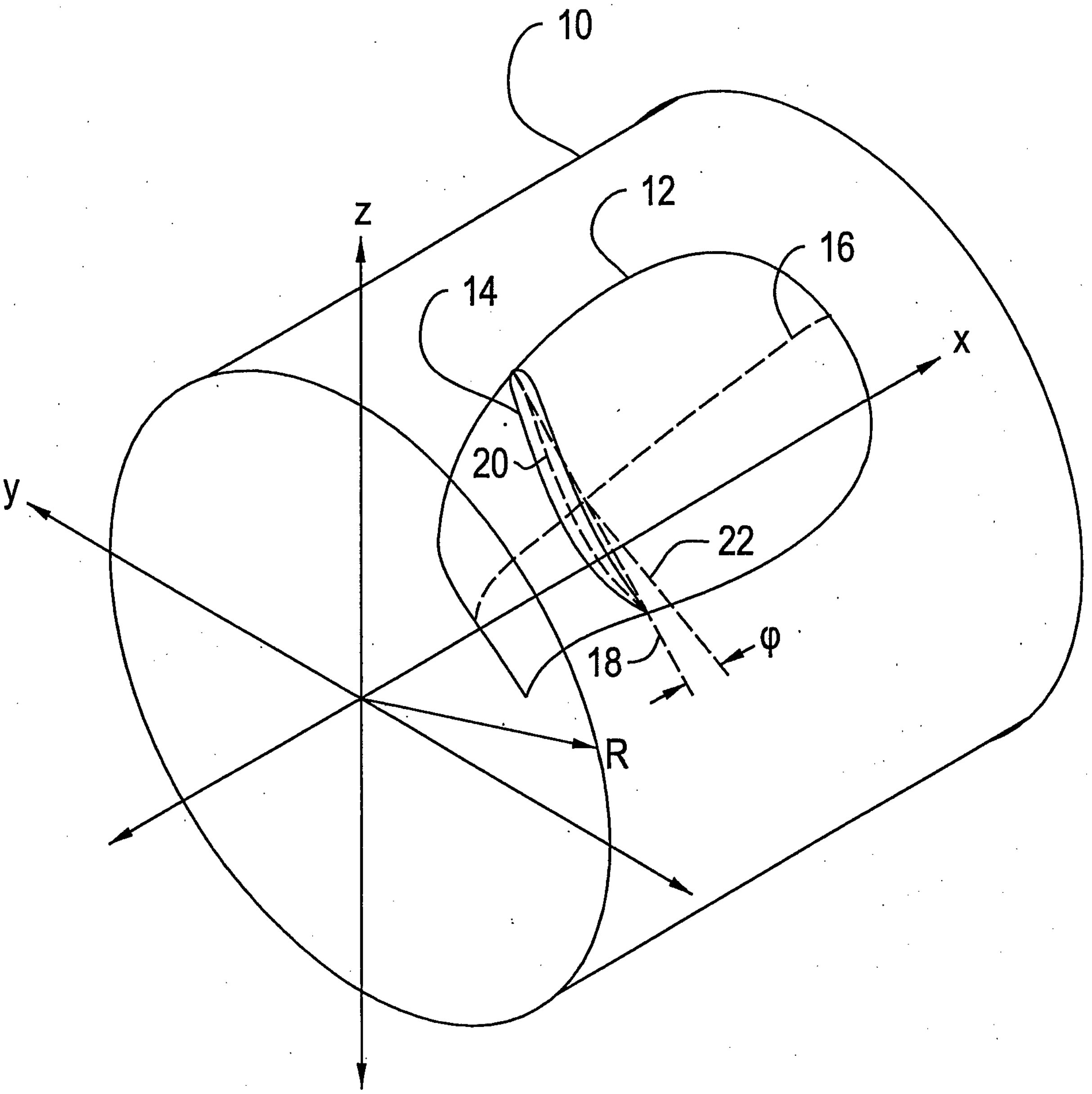
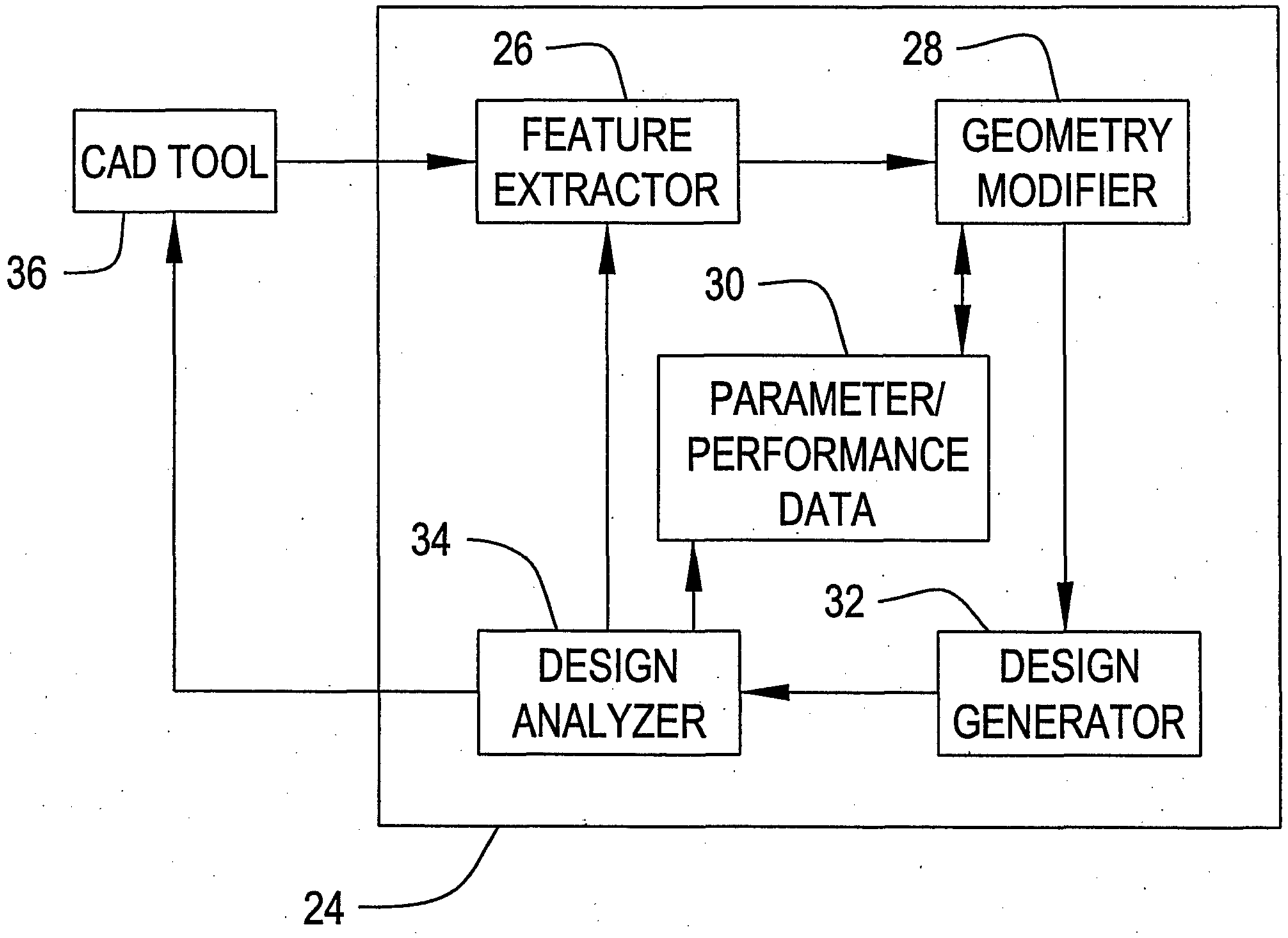


FIG. 1
(PRIOR ART)



CAD TOOL
36
26
FEATURE EXTRACTOR
28
GEOMETRY MODIFIER
30
PARAMETER/ PERFORMANCE DATA
34
DESIGN ANALYZER
32
DESIGN GENERATOR
24

FIG. 2

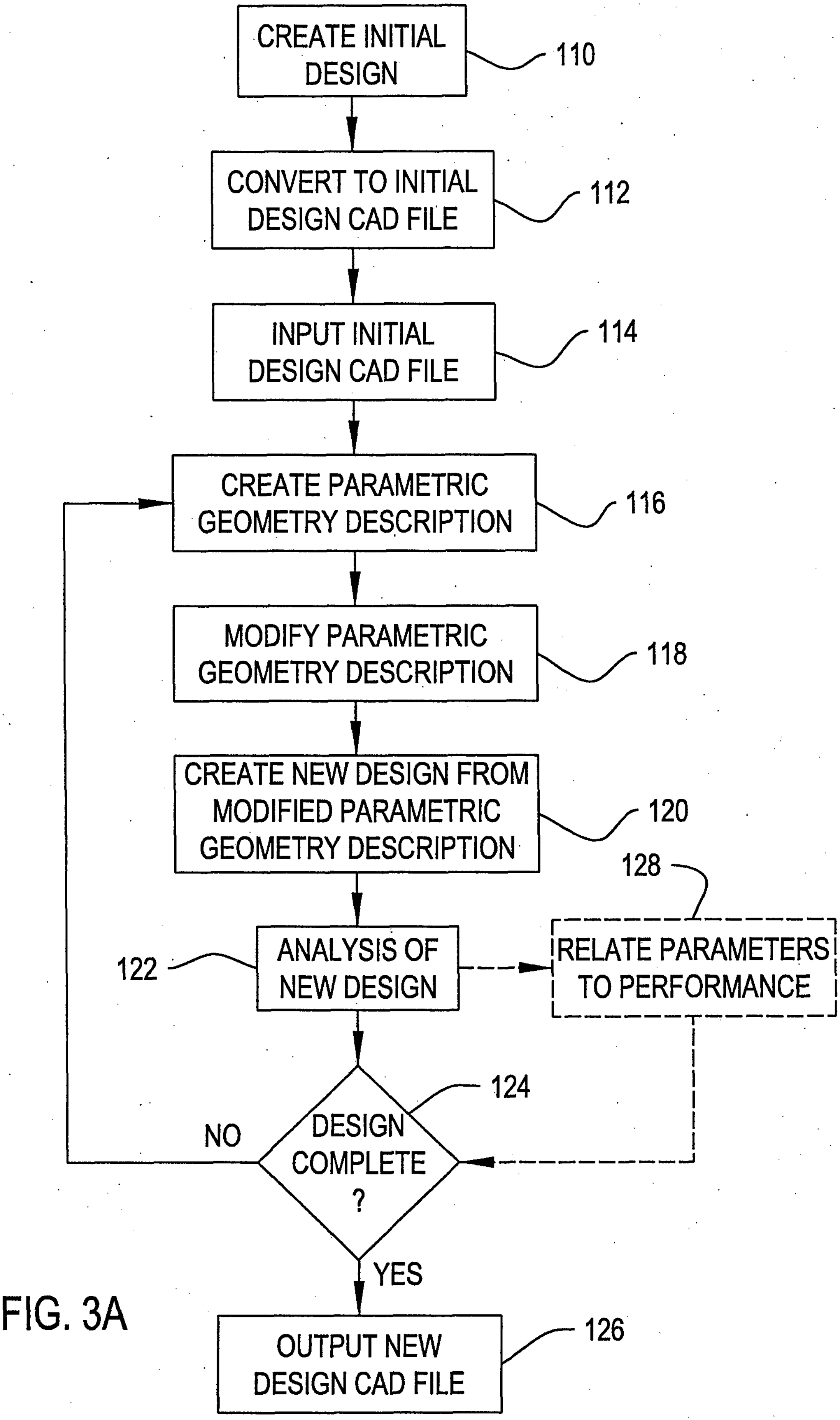

CREATE INITIAL DESIGN
110
CONVERT TO INITIAL DESIGN CAD FILE
112
INPUT INITIAL DESIGN CAD FILE
114
CREATE PARAMETRIC GEOMETRY DESCRIPTION
116
MODIFY PARAMETRIC GEOMETRY DESCRIPTION
118
CREATE NEW DESIGN FROM MODIFIED PARAMETRIC GEOMETRY DESCRIPTION
120
128
122
ANALYSIS OF NEW DESIGN
RELATE PARAMETERS TO PERFORMANCE
124
NO
DESIGN COMPLETE ?
YES
126
OUTPUT NEW DESIGN CAD FILE

FIG. 3A

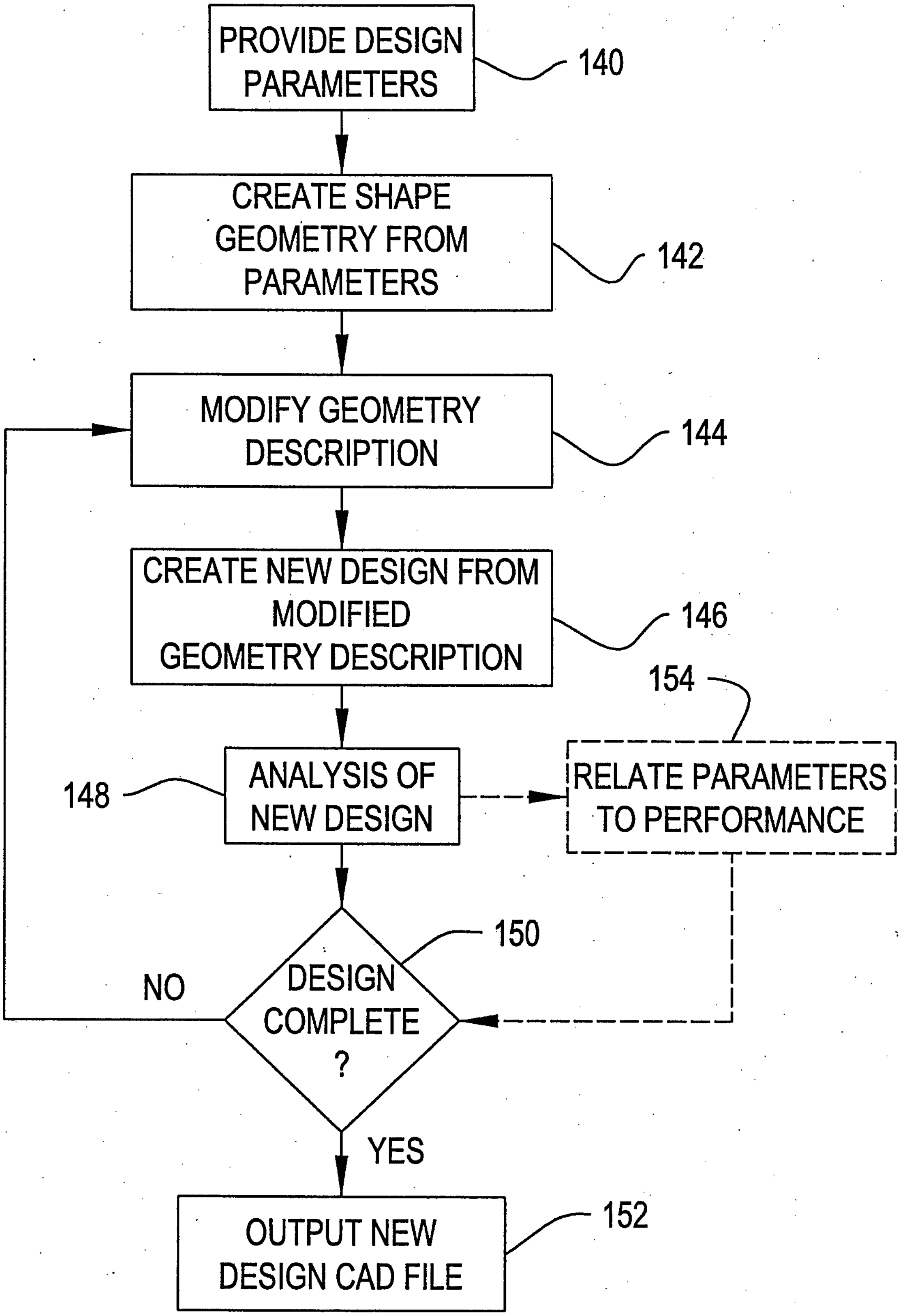

PROVIDE DESIGN PARAMETERS
140
CREATE SHAPE GEOMETRY FROM PARAMETERS
142
MODIFY GEOMETRY DESCRIPTION
144
CREATE NEW DESIGN FROM MODIFIED GEOMETRY DESCRIPTION
146
154
148
ANALYSIS OF NEW DESIGN
RELATE PARAMETERS TO PERFORMANCE
150
NO
DESIGN COMPLETE ?
YES
OUTPUT NEW DESIGN CAD FILE
152

FIG. 3B

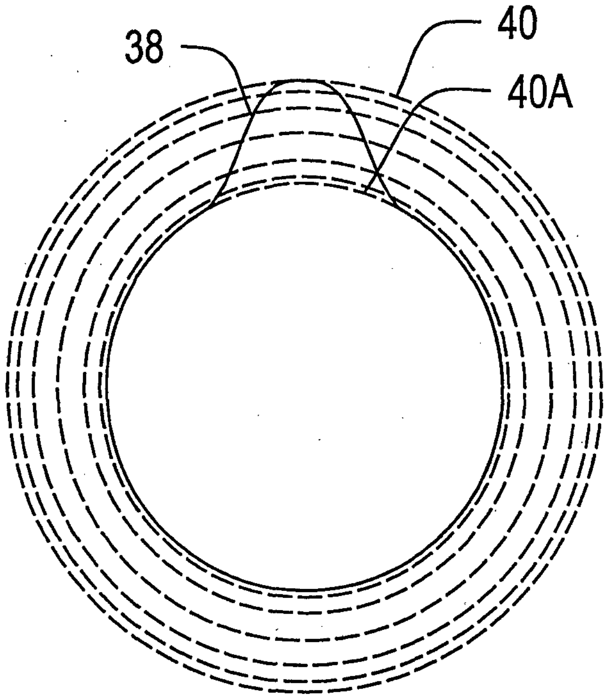

38
40
40A

FIG. 4

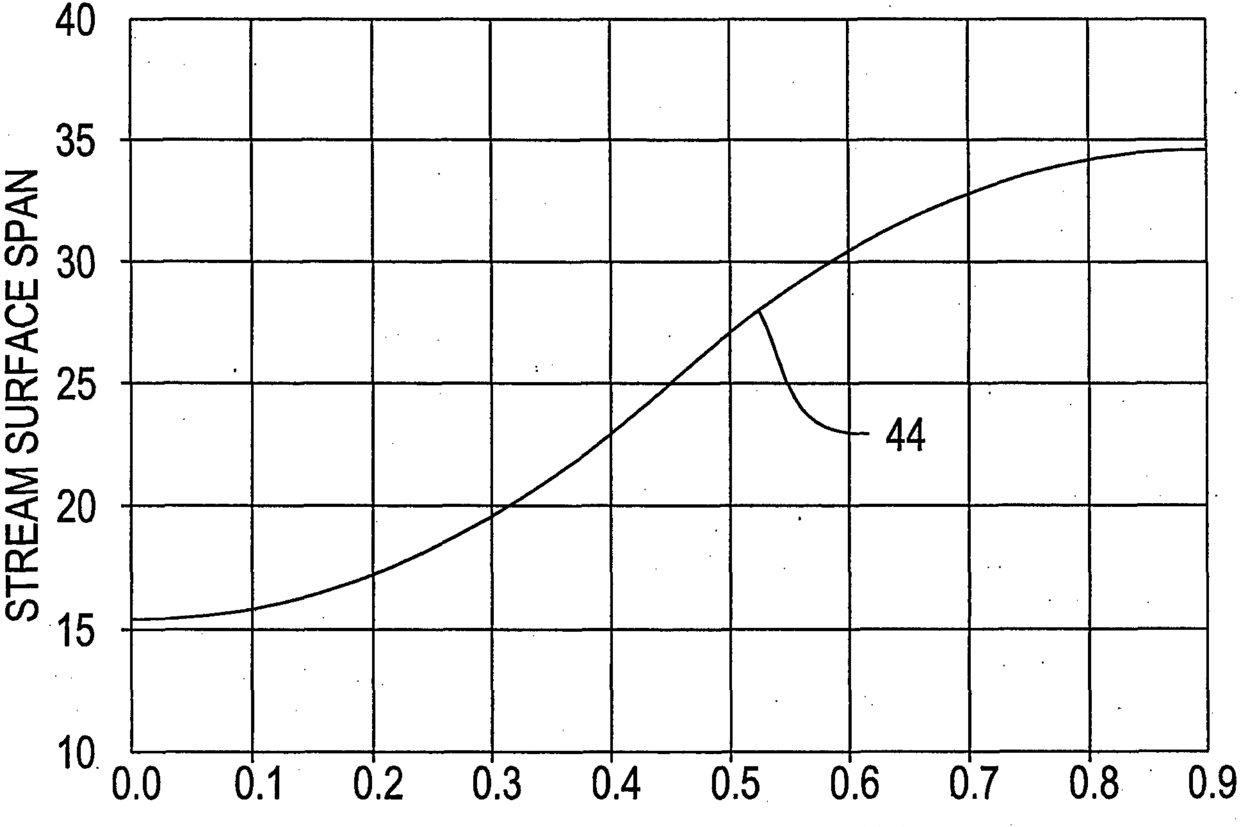

40
35
30
25
20
15
10
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
STREAM SURFACE SPAN
STREAM SURFACE PARAMETER
44

FIG. 5

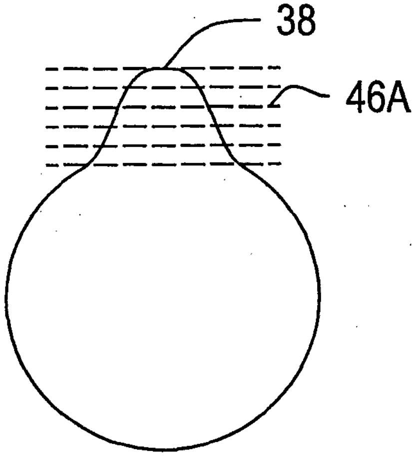


FIG. 6A

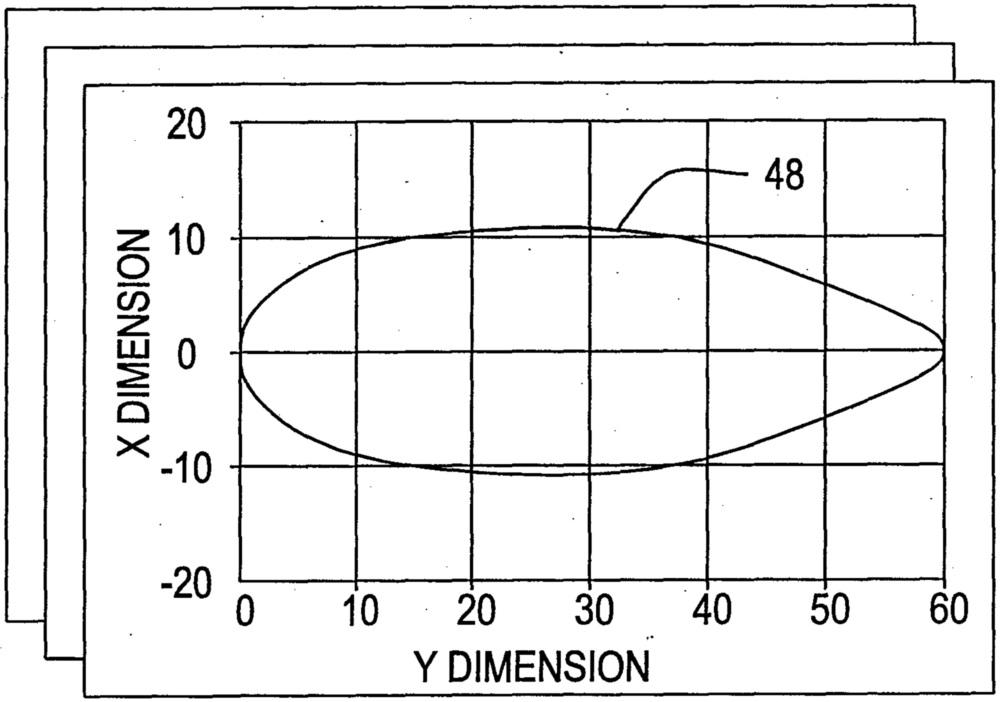


FIG. 7

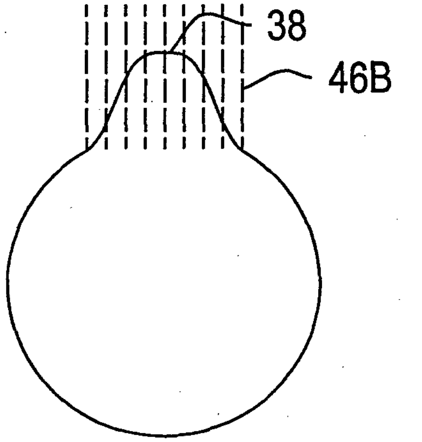


FIG. 6B

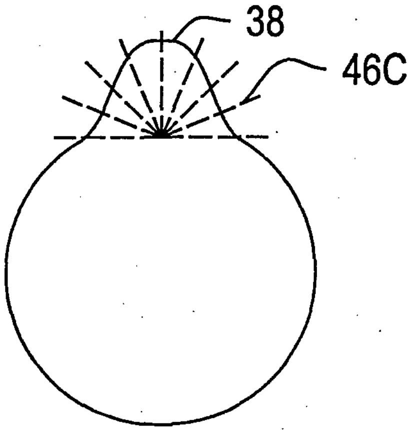


FIG. 6C

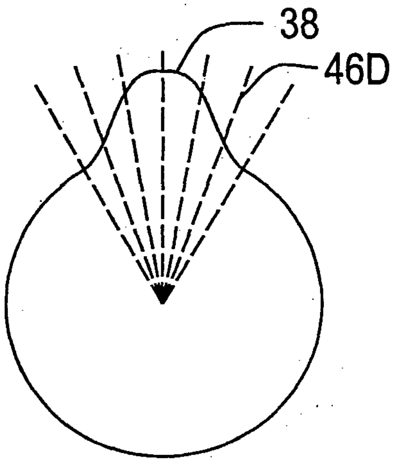


FIG. 6D