(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
2 May 2013 (02.05.2013)

WIPO | PCT

(10) International Publication Number
WO 2013/062697 A1

(51) International Patent Classification:
G06F 17/50 (2006.01)

(21) International Application Number:
PCT/US2012/056402

(22) International Filing Date:
20 September 2012 (20.09.2012)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:
61/550,429 23 October 2011 (23.10.2011) US
13/310,665 2 December 2011 (02.12.2011) US

(71) Applicant: **THE BOEING COMPANY** [US/US]; 100 North Riverside Plaza, Chicago, Illinois 60606-2016 (US).

(72) Inventors; and
(71) Applicants : **GRANDINE, Thomas A.** [US/US]; The Boeing Company, Post Office Box 3707, Seattle, Washington 98124 (US). **PATTERSON, Matthew S.** [US/US]; The Boeing Company, 2760 160th Avenue Southeast, Bellevue, Washington 98008 (US).

(74) Agents: **SOUCY, Kathryn** et al.; The Boeing Company, PO Box 2515, MC 110-SD54, Seal Beach, California 90740-1515 (US).

(81) Designated States *(unless otherwise indicated, for every kind of national protection available)*: AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IS, JP, KE, KG, KM, KN, KP, KR, KZ, LA, LC, LK, LR, LS, LT, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ, OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SC, SD, SE, SG, SK, SL, SM, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, ZA, ZM, ZW.

(84) Designated States *(unless otherwise indicated, for every kind of regional protection available)*: ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:

— *with international search report (Art. 21(3))*

WO 2013/062697 A1

(54) Title: GEOMETRIC MODELING OF A COMPOSITE PART INCLUDING A PLY-STACK UP AND RESIN

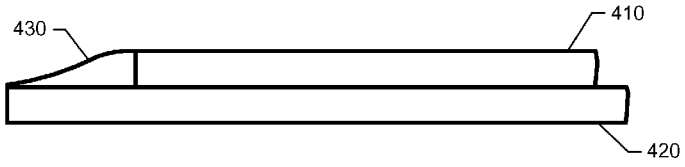


FIG. 4

(57) Abstract: A composite part including a ply stack-up and resin is modeled. The modeling includes performing a convolution on a representation of the stack-up to approximate smoothed ramps between different plies of the stack-up.

GEOMETRIC MODELING OF A COMPOSITE PART INCLUDING A PLY- STACK UP AND RESIN

BACKGROUND

Composites are attractive to the aerospace industry because of their high strength, high rigidity, and low weight. A composite structure such as skin or a stiffener may be constructed by stacking up plies of resin-infused carbon fiber tape or fabric on a mandrel, forming an air-tight envelope over the ply stack-up, and curing the stack-up.

Weight reduction in an aircraft is highly desirable, as it reduces aircraft operating costs. The weight of composite aircraft parts may be reduced by using composite material where needed. Skin may be formed from an outer ply. Pad-ups on the skin may be used to increase thickness at locations where fasteners will be installed or extra strength is needed. In a complex structure such as a composite fuselage, the skin may have an overall nominal thickness, which is padded up to various degrees over arbitrary areas for strength or gage.

A ply stack-up may have a step-like geometry. Prior to curing, edges of the ply stack-up are sharp. During curing, pre-impregnated resin flows through the stack-up, forming ramps off the edges, which transition from one ply to the next. A complex structure such as a fuselage may have tens of thousands of edges.

In the aircraft industry, it is useful to model the geometry of composite parts. The geometric model may be used to determine material properties (e.g., stresses, strains, and displacement) for the composite parts, generate tape laying sequences, and create automated NC part programs.

SUMMARY

According to an embodiment herein, a composite part including a ply stack-up and resin is modeled. The modeling includes performing a convolution on a representation of the stack-up to approximate smoothed ramps between different plies of the stack-up.

According to another embodiment herein, an apparatus comprises a computer programmed to model a composite part including a ply stack-up and resin. The modeling includes performing a convolution on a representation of the stack-up to approximate smoothed ramps between different plies of the stack-up.

According to another embodiment herein, an article comprises non-transitory computer memory programmed with data for causing a computer to model a composite part including a ply stack-up and resin. The modeling includes performing a convolution on a representation of the stack-up to approximate smoothed ramps between different plies of the stack-up.

One aspect of the present disclosure relates to a method of modeling a composite part including a ply stack-up and resin. The method includes using a computer to perform a convolution on a representation of the stack-up to approximate smoothed ramps between different plies of the stack-up.

In one example, the method also includes contouring the representation of the stack-up prior to the convolution.

In one variant, the method also includes contouring the representation of the stack-up after the convolution.

In one alternative of the method, the representation of the stack-up is contoured with a surface that is modeled procedurally.

In another example of the method, a top ply of the representation corresponds to a mold line ply of the stack-up.

In another variant of the method, a top ply of the representation corresponds to an intermediate ply of the stack-up.

In another alternative of the method, the representation identifies thickness of the stack-up at discrete points on a defining surface of the stack-up.

In yet another example of the method, the representation identifies thousands of edges.

In yet another variant of the method, the convolution is performed with a kernel that is volume-conserving.

In yet another alternative of the method, the convolution is performed with a B-spline convolution kernel.

In still another example of the method, distance of knots from a center of the kernel corresponds to how the resin flows from edges of the stack-up.

In still another variant of the method, the convolution is performed as

$$\int_{-\infty}^{\infty} Z(t \mid x_0,\ldots,x_n) M(x-t \mid y_0,\ldots,y_m) dt$$

where Z is a piecewise constant function that defines a normal component of a 2D ply stack-up, and M is a B-spline convolution kernel defined by its knots and

order.

In still another alternative of the method, the convolution is performed with a kernel that is chosen according to characteristics of the resin.

In still yet another example of the method, the part is a fuselage part of a commercial aircraft.

In still yet another variant, the method also includes using a result of the convolution to define geodesics for tape laying for the composite part.

In still yet another alternative, the method also includes using a result of the convolution to develop a tool side surface for the composite part.

In a further example, the method also includes using a result of the convolution for flat patterning of the composite part.

Another aspect of the present disclosure relates to an apparatus that includes a computer programmed to model a composite part including a ply stack-up and resin. The modeling includes performing a spline convolution on a representation of the stack-up to approximate smoothed ramps between different plies of the stack-up.

In one example of the apparatus, the convolution is performed with a B-spline convolution kernel having a knot structure that represents how the resin flows from edges of the stack-up.

Yet another aspect of the present disclosure relates to an article that includes non-transitory computer memory programmed with data for causing a computer to model a composite part including a ply stack-up and resin. The modeling includes performing a spline convolution on a representation of the stack-up to approximate smoothed ramps between different plies of the stack-up.

The terms “example”, “variant”, and “alternative” hereinabove are used interchangeably.

These features and functions may be achieved independently in various embodiments or may be combined in other embodiments. Further details of the embodiments can be seen with reference to the following description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 is an illustration of a ply stack-up.

FIGS. 2A-2C are illustrations of methods of modeling a composite part including a ply stack-up and resin.

FIGS. 3A-3D are illustrations of a method of modeling a composite part including a ply stack-up and resin.

FIG. 4 is an illustration of a resin ramp from a first ply to a second ply.

FIG. 5 is an illustration of a method of using a model of a composite part to improve fabrication of the part.

FIG. 6 is an illustration of a machine for modeling a composite part including a ply stack-up and resin.

FIG. 7 is an illustration of an aircraft including parts that may be modeled according to embodiments herein.

DETAILED DESCRIPTION

Reference is made to FIG. 1, which illustrates a ply stack-up 110 prior to curing. The stack-up 110 includes a plurality of plies of resin-infused fibers (e.g., between 10 and 100 plies). The fibers may be applied as tape or fabric. The plies may be stacked normal to an outside surface. The stack-up 110 has a step-like geometry. Pre-cured edges of the stack-up 110 are sharp.

In the design of composite aircraft parts, the stack-up 110 may be designed from the outer (e.g., aero) surface toward the inner surface. The stack-up 110 may be manufactured in the opposite direction (the aero surface is last to be deposited). For parts involving an outer mold line (i.e., an exterior surface of an aircraft), those parts may be designed from the outer mold line inwards towards an inner mold line. For manufacturing, the opposite may be true, especially for large structures such as fuselages, where the plies are built-up from the inner mold line outwards. The arrows in FIG. 1 are not always true for all aircraft parts (for instance, wing skins may be designed and built from the outer mold line inward toward the inner mold line). However, the arrows are intended to represent that the outer mold line may be the design surface and the inner mold line may be a tooling surface.

Reference is now made to FIG. 2A, which illustrates a method of modeling a composite part including a ply stack-up and resin. At block 210, a discrete representation of the ply stack-up (the “discrete correction”) is accessed. The discrete correction identifies thickness of the ply stack-up at any point on its defining surface (e.g., inner or outer surface). A complex structure such as a fuselage may have tens of thousands of edges. In some embodiments, the discrete correction may be a piecewise constant function.

The discrete correction may be derived from an engineering definition of the part. The engineering definition may define surface geometry including contour and features such as holes, trim locations, and engineering edge of part. The

engineering definition may also specify ply drops, ply boundaries, stacking sequence and fiber orientations within each ply. The engineering definition may define material specifications for the composite part. Software may be designed to produce the discrete representation of the stack-up by counting plies at a large number of points on the defining surface.

At block 220, a convolution is performed on the discrete representation of the stack-up. The convolution "softens" the edges and approximates a smoothed ramp between different plies of the stack-up. These smoothed ramps represent resin after curing. (During curing, the pre-impregnated resin will flow through the stack-up, forming ramps off the edges, which transition from one ply to the next.) The result of the convolution is an empirical approximation of a cured stack-up.

In practice, a stack-up will be contoured prior to curing. For instance, if the tooling surface is curved, the stack-up will be contoured according to the curve of the tooling surface.

FIGS. 2B and 2C illustrate two different ways in which the empirical approximation may be contoured. The contouring may be performed after convolution (FIG. 2B) or prior to convolution (FIG. 2C). A contour may be defined by a surface model. In some embodiments, the surface model represents a tool surface (that is, the surface upon which the plies will be stacked up), which gives a contour to the cured part. In other embodiments, the surface model may represent a mating surface with another part (that is surfaces to which the composite part will be attached), an outer mold line, or any other pre-defined surface.

In some embodiments, the surface may be modeled as a spline. In other embodiments, surface may be modeled as primitives such as cones, spheres, planes, or a combination thereof them.

In still other embodiments, the surface may be modeled procedurally. For example, a surface is mapped over a domain, where different portions of the domain are mapped in different ways. For instance, the surface is mapped to a spline or a primitive (e.g., a portion of a cylinder) over one portion of the domain, and the surface is mapped to a fillet having a prescribed radius over the remainder of the domain (e.g., at edges of a member).

Reference is made to FIG. 2B, which illustrates the first way in which the discrete correction is contoured after convolution. At block 250, a convolution is performed on the discrete representation of the stack-up to approximate smoothed

ramps between different plies of the stack-up.

At block 260, the empirical approximation produced by the convolution is added to the surface model. The empirical approximation may be added to the surface model as $S(u,v)=T(u,v)+\hat{Z}(u,v)N(u,v)$, where

(u,v) represents the position of a point in a unit square;

$S(u,v)$ represents the empirical approximation that is contoured according to the surface model;

$T(u,v)$ represents the surface model, which may be a mapping from a unit square into 3D space so that points (u,v) in the unit square are mapped to points $T(u,v)$ on the surface;

$Z(u,v)$ is the discrete correction;

$\hat{Z}(u,v)$ is the convolution of the discrete correction; and

$N(u,v)$ is the surface normal.

Reference is made to FIG. 2C, which illustrates the second way in which the empirical approximation is contoured prior to convolution. At block 280, the discrete representation of the ply stack-up is combined with the surface model. Thus, the discrete correction is contoured.

At block 290, a convolution is performed on the contoured correction.

The convolution is applied only to the correction, not to the surface model. During curing of a part in an autoclave, for instance, the tooling surface isn't changed by the applied heat and pressure.

FIGS. 3A-3D illustrate the method of FIG. 2C. A contoured underlying surface 310 (e.g., a tooling surface) is illustrated in FIG. 3A, and a 2D stack-up 320 including three plies is illustrated in FIG. 3B. A combined representation 130 of the stack-up 320 on the contoured surface 310 is illustrated in FIG. 3C. In this combined representation 130, the stack-up 320 is located on the surface 310, and the edges of the stack-up 320 are sharp. The stack-up 320 follows the contour of the underlying surface 310.

FIG. 3D illustrates the approximation 340 resulting from the convolution on the contoured discrete correction. Resin ramps are formed from the third ply to the second ply, from the second ply to the first ply, and from the first ply to the surface 310.

FIG. 4 illustrates a resin ramp 410 that transitions from a first ply 420 to a second ply 430.

The convolution is performed with a kernel. As but one example, the convolution may be performed with a B-spline convolution kernel. The B-spline kernel is defined by its knots and its order. The convolution may be performed as

$$\int_{-\infty}^{\infty} Z(t \mid x_0,\ldots,x_n)M(x-t \mid y_0,\ldots,y_m)dt$$

where *Z* is a piecewise constant function that defines the normal component of a 2D ply stack-up, and *M* is a B-spline convolution kernel defined by its knots and order.

In designing the kernel, knot structure is constructed, and the order is selected. The order determines the amount of smoothing. The knot structure and order fix the coefficients of the kernel. The knot structure affects the modeling of the movement of resin. Roughly speaking, the farther knots are located from the center of the kernel, the more flow that is represented.

In some embodiments, the kernel may be volume-preserving. A volume preserving kernel is a kernel that integrates to unity over the entire domain. When it is applied through a convolution operator, the integral of the original object remains unchanged. In the case of a convolution, this means that the volume of the composite part does not change.

However, the kernel is not limited to one that is volume-preserving. Using non-volume preserving kernels enables modeling the situation in which compression of material occurs during curing.

In some embodiments, a choice of kernels may be available, and the convolution is performed with a kernel that is chosen according to characteristics of the resin. For example, a selection may be made between a first kernel corresponding to a first type of resin and a second kernel corresponding to another type of resin that flows more freely and is more likely to form a longer ramp. The different kernels may be distinguished by different knot structures, or different types of kernels may be used. Examples of other types of kernels include Gaussian distributions and probability density functions. However, the B-spline is faster than these other kernels, and since the B-spline is dense within space, it can be configured to model different flows of resin.

Reference is now made to Figure 5. The modeling herein (block 510) may be used advantageously to improve composite fabrication processes. As a first example, the modeling herein may be used to develop tool side surfaces (block 520). Starting with an exterior surface, plies are continually added and smoothed until a

tool side surface is obtained. These tool side surfaces may be used to machine molds.

As a second example, modeling of an intermediate layer of a stack-up may be used to improve flat patterning (block 530). For instance, if the empirical approximation reveals that a ply extends beyond the resin ramp, that ply may be shortened. If the empirical approximation reveals that the ply is too short, the ply may be lengthened.

As a third example, the modeling may be used to reduce the uncertainty of weight computations. The modeling may reduce uncertainty over the amount or resin, length and thickness of the plies (which affects the ply weight), center of gravity, and moments of inertia etc.

As a fourth example, the modeling may be used to infer tape laying sequencing (block 550). The modeling provides smooth surfaces over which geodesics can be computed reliably and accurately. These geodesics form the basis of computations which improve tape laying operations, including sequencing and orientation and steering of tape laying heads.

A method herein is not limited to modeling the final surface of a composite part. In some embodiments, a method herein may be used for the modeling of intermediate or partial ply stack-ups. Intermediate ply locations may be useful for providing repair schematics and performing mass property calculations for non-homogeneous ply stacks, both of which require models for cured partial ply stacks. An intermediate ply may be modeled simply by leaving off all plies above that intermediate ply.

Reference is now made to FIG. 6, which illustrates a machine 610 including a processor 620, and non-transitory machine-readable memory 630. In some embodiments, the machine 610 may be a computer. A program 640 is stored in the memory 630. When executed in the machine 610, the program 640 performs modeling of one or more composite parts as described herein.

Reference is made to FIG. 7, which illustrates an example of a composite aircraft 700. The aircraft 700 includes components and parts thereof that may be modeled according to a method herein. The components may include, but are not limited to a fuselage 710, wing assemblies 720, empennage 730, and landing gear assemblies 740.

THE CLAIMS

1. A method of modeling a composite part including a ply stack-up (110) and resin, the method comprising using a computer (610) to perform a convolution on a representation (130) of the stack-up (110) to approximate smoothed ramps between different plies of the stack-up (110).

2. The method of claim 1, further comprising contouring the representation (130) of the stack-up (110) prior to the convolution.

3. The method of claim 1, further comprising contouring the representation (130) of the stack-up (110) after the convolution.

4. The method of any of claims 1-3, wherein a top ply of the representation (130) corresponds to a mold line ply of the stack-up (110).

5. The method of any of claims 1-3, wherein a top ply of the representation (130) corresponds to an intermediate ply of the stack-up (110).

6. The method of any of claims 1-5, wherein the representation (130) identifies thickness of the stack-up (110) at discrete points on a defining surface of the stack-up (110).

7. The method of any of claims 1-6, wherein the convolution is performed with a kernel that is volume-conserving.

8. The method of any of claims 1-6, wherein the convolution is performed with a B-spline convolution kernel.

9. The method of claim 8, wherein the convolution is performed as

$$\int_{-\infty}^{\infty} Z(t \mid x_0,\ldots,x_n) M(x-t \mid y_0,\ldots,y_m) dt$$

where *Z* is a piecewise constant function that defines a normal component of a 2D ply stack-up (320), and *M* is a B-spline convolution kernel defined by its knots and order.

10. The method of any of claims 1-9, further comprising using a result of the convolution to define geodesics for tape laying for the composite part.

11. The method of any of claims 1-10, further comprising using a result of the convolution to develop a tool side surface (520) for the composite part.

12. The method of any of claims 1-11, further comprising using a result of the convolution for flat patterning (530) of the composite part.

13. An apparatus comprising a computer (610) programmed to model a composite part including a ply stack-up (110) and resin, the modeling including performing a spline convolution on a representation (130) of the stack-up (110) to approximate smoothed ramps between different plies of the stack-up (110).

14. The apparatus of claim 13, wherein the convolution is performed with a B-spline convolution kernel having a knot structure that represents how the resin flows from edges of the stack-up (110).

15. An article comprising non-transitory computer memory (630) programmed with data for causing a computer (610) to model a composite part including a ply stack-up (110) and resin, the modeling including performing a spline convolution on a representation (130) of the stack-up (110) to approximate smoothed ramps between different plies of the stack-up (110).

FIG. 1

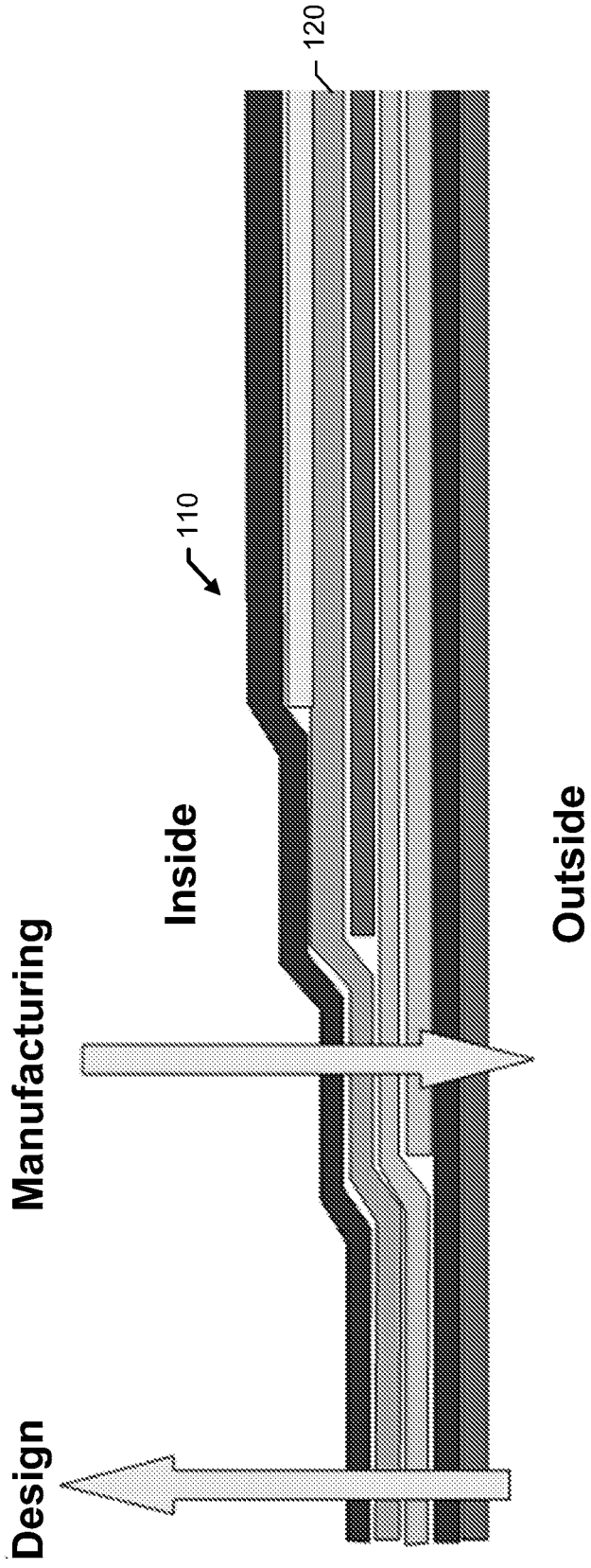


FIG. 2A

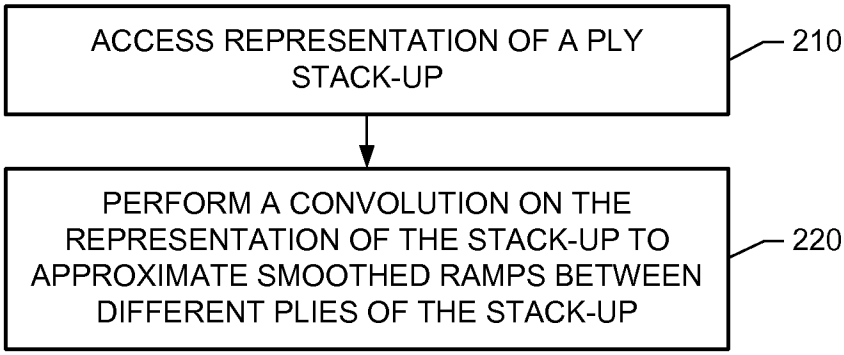


FIG. 2B

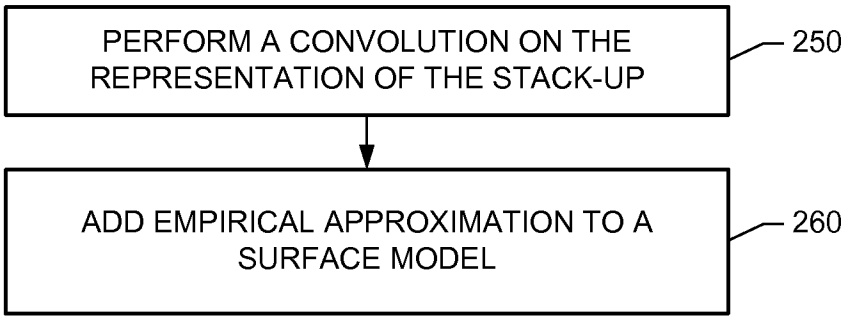
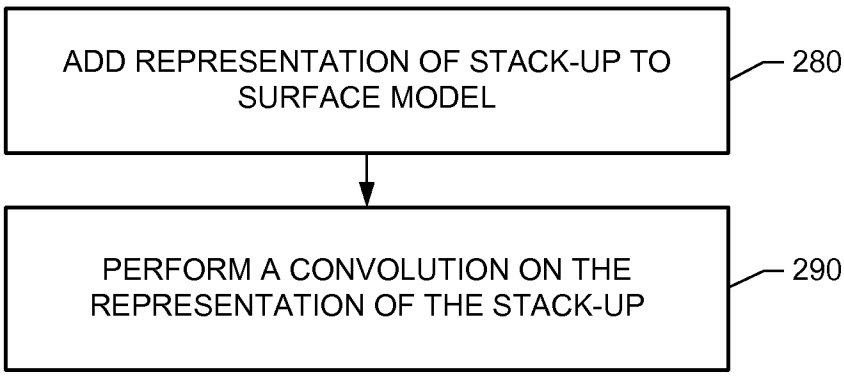


FIG. 2C



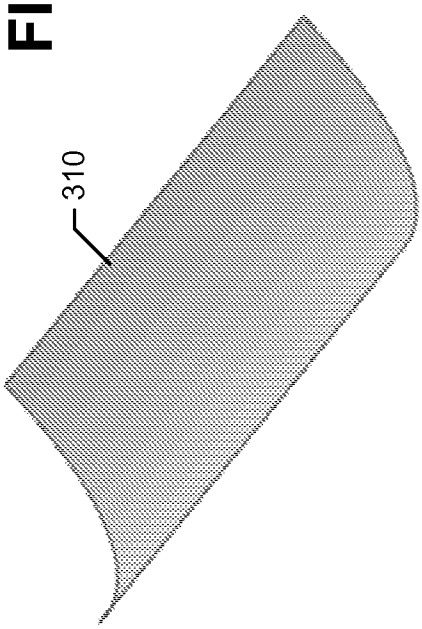


FIG. 3A

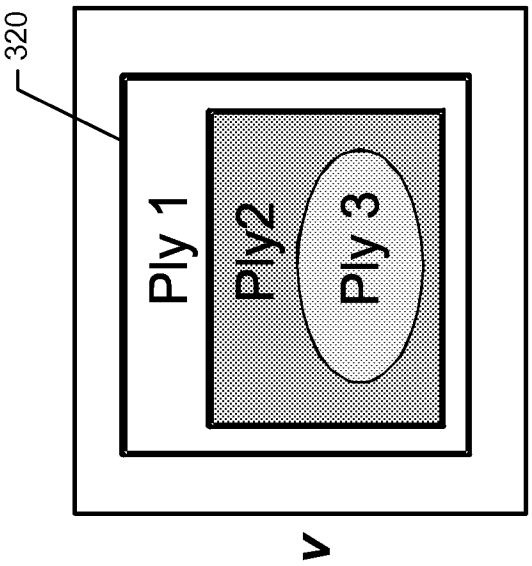


FIG. 3B

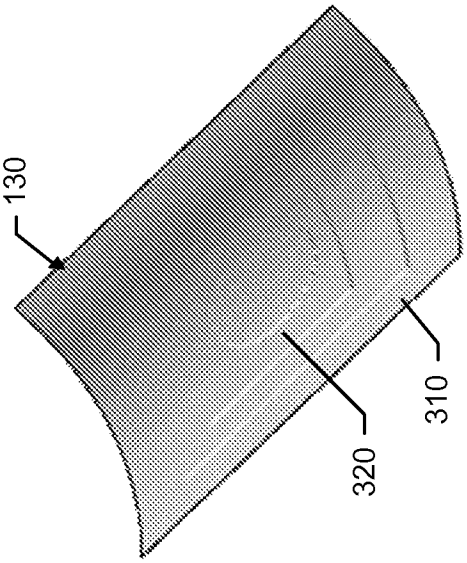
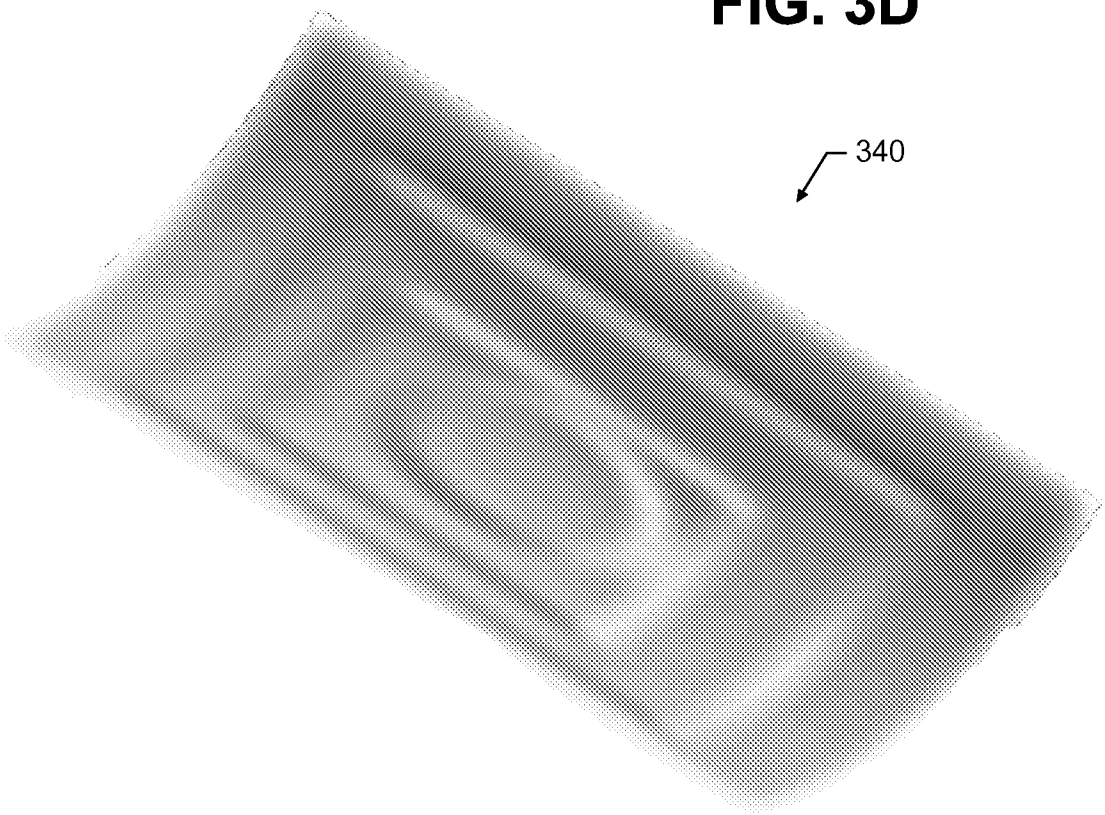


FIG. 3C

FIG. 3D



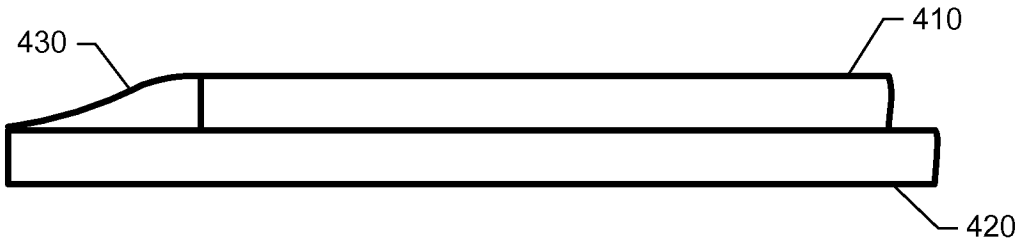
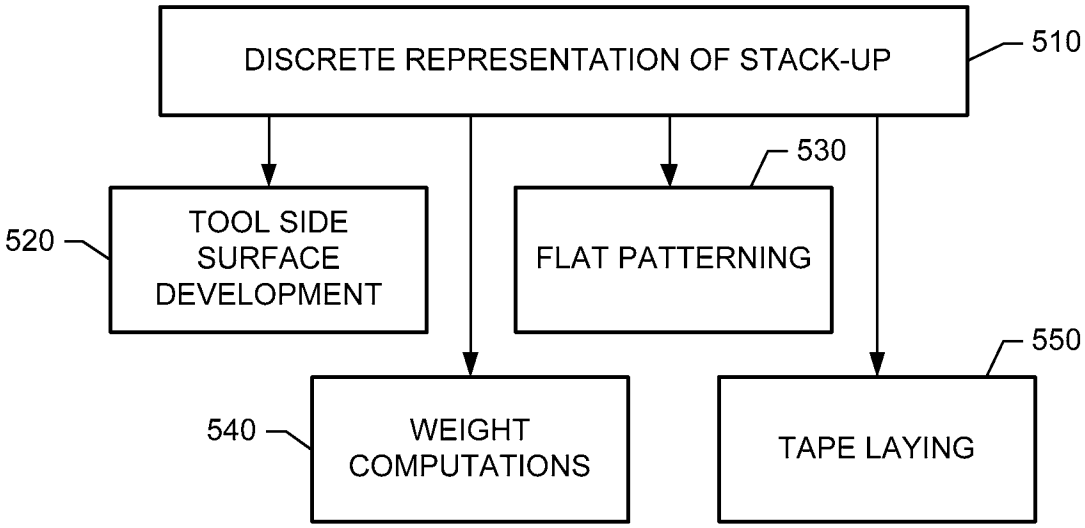


FIG. 4

FIG. 5


DISCRETE REPRESENTATION OF STACK-UP
510
TOOL SIDE SURFACE DEVELOPMENT
520
FLAT PATTERNING
530
WEIGHT COMPUTATIONS
540
TAPE LAYING
550

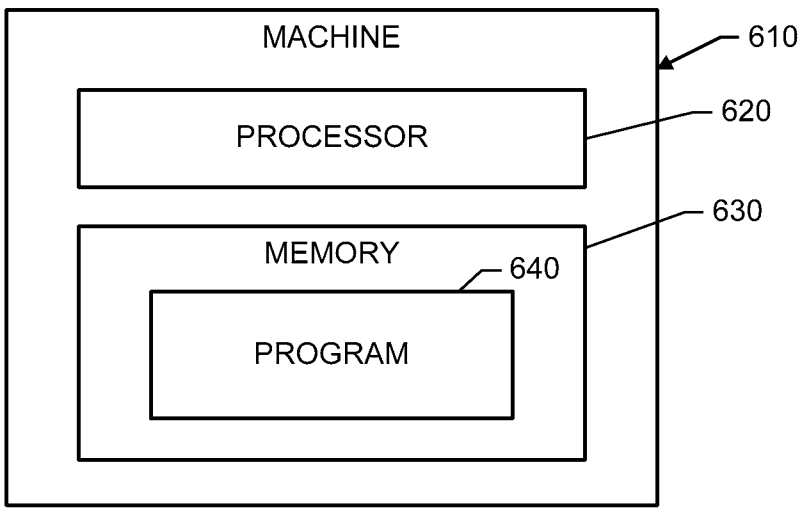
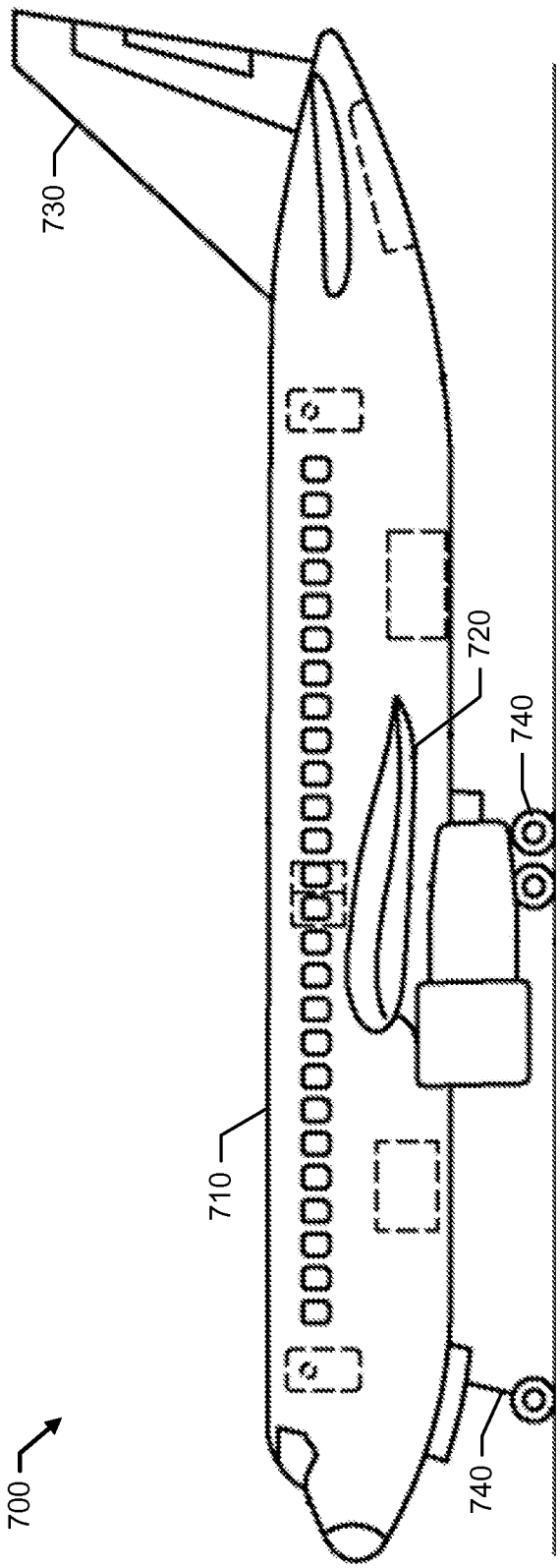

MACHINE
610
PROCESSOR
620
MEMORY
630
PROGRAM
640

FIG. 6

FIG. 7



INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/056402

A. CLASSIFICATION OF SUBJECT MATTER
INV. G06F17/50
ADD.

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
G06F

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
EPO-Internal

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US 2008/312764 A1 (MURRISH RICHARD E [US]) 18 December 2008 (2008-12-18) the whole document, in particular paragraphs [0032], [0037] and claims 8, 21.	1-15
Y	G. SEALY ET AL: "Smoothing of three dimensional models by convolution", PROCEEDINGS OF CG INTERNATIONAL '96, 1 January 1996 (1996-01-01), pages 184-190, XP55050541, DOI: 10.1109/CGI.1996.511800 ISBN: 978-0-81-867518-8 the whole document, in particular the abstract and section 2. Convolution	1-15

-/--

[X] Further documents are listed in the continuation of Box C.

[X] See patent family annex.

* Special categories of cited documents :

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
22 January 2013	31/01/2013

Name and mailing address of the ISA/	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Fax: (+31-70) 340-3016	Lerbinger, Klaus

INTERNATIONAL SEARCH REPORT

International application No
PCT/US2012/056402

C(Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	ANDREI SHERSTYUK: "Kernel functions in convolution surfaces: a comparative analysis", THE VISUAL COMPUTER, vol. 15, no. 4, 7 July 1999 (1999-07-07), pages 171-182, XP055050563, ISSN: 0178-2789, DOI: 10.1007/s003710050170 the whole document -----	1-15

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No
PCT/US2012/056402

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2008312764 A1	18-12-2008	US 2008312764 A1	18-12-2008
		WO 2008157364 A1	24-12-2008