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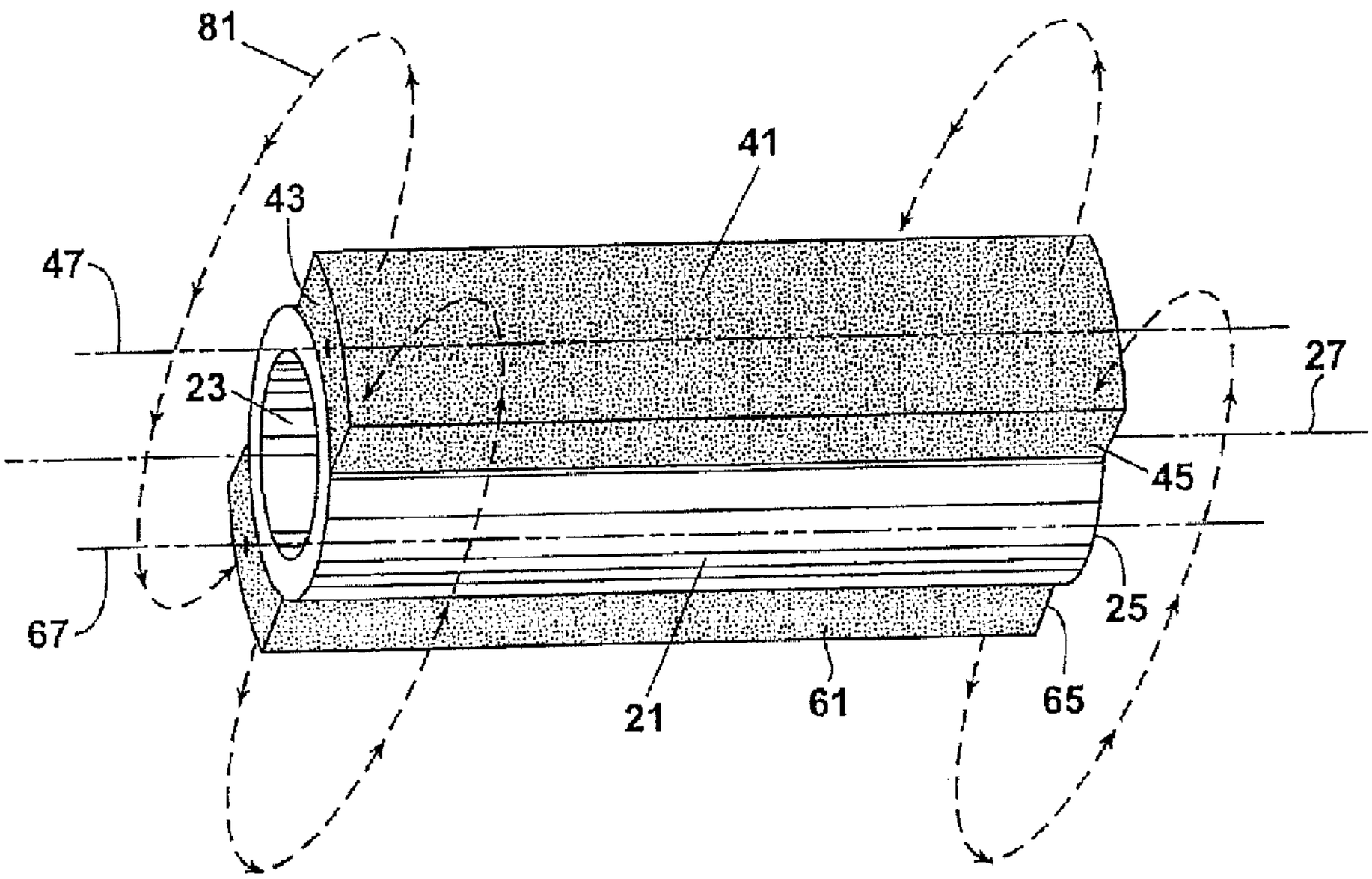
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(57) Abrégé/Abstract:
A pipeline inspection tool has an even number of pole magnets, each spiraled about the tool body so that a second end of each magnet is offset amount "α" relative to a first end. The rotation α applied to the magnets produces a magnetic field oblique to the longitudinal body axis. In another aspect, the tool includes two pole magnets oriented at an oblique angle relative to the longitudinal axis body. An array of sensor coil sets is located between opposing edges of the two magnets and oriented perpendicular to the axis. Each set includes a transmitter coil and two opposing pairs of receiver coils that are gated to receive reflections from the wall of a tubular member. Because the line of coils is rotated relative to the magnetic bias field, the receiver coils are in-line with, and have the same angular orientation as, the transmitter coil.

ABSTRACT OF THE DISCLOSURE

A pipeline inspection tool has an even number of pole magnets, each spiraled about the tool body so that a second end of each magnet is offset amount "α" relative to a first end. The rotation α applied to the magnets produces a magnetic field oblique to the longitudinal body axis. In another aspect, the tool includes two pole magnets oriented at an oblique angle relative to the longitudinal axis body. An array of sensor coil sets is located between opposing edges of the two magnets and oriented perpendicular to the axis. Each set includes a transmitter coil and two opposing pairs of receiver coils that are gated to receive reflections from the wall of a tubular member. Because the line of coils is rotated relative to the magnetic bias field, the receiver coils are in-line with, and have the same angular orientation as, the transmitter coil.

PIPELINE INSPECTION TOOL

Field of Invention

This invention relates generally to inspection tools designed to detect anomalies in tubing, piping and pipelines and, more particularly, to inline inspection tools employing magnetic flux leakage detection techniques.

Background of the Invention

Many installed pipelines may be inspected using the Magnetic Flux Leakage (MFL) technique, primarily for the purpose of identifying metal loss anomalies. Magnetic flux leakage has been shown to respond in predictable ways to anomalies in the wall of the pipeline as the principal axis of the metal loss anomaly and field angle are varied. Both experimental and modeling results have been used to confirm this effect, which is also widely described in the literature.

Due in part to limitations imposed by data acquisition, data storage and magnetic circuit designs, most in-line inspection tools have employed axially oriented magnetizers (see

e.g., U.S. Pat. No. 6,820,653 to Schempf et al.). However, the present axial field magnetizer designs make identification and quantification of extremely narrow axial features difficult, or in some cases, impossible. For these feature classes, a solution using a magnetic field in the circumferential or transverse direction, have been marketed and placed in service over the past decade by pipeline inspection providers. However, due to the constraints of physics, the performance and accuracy of these transverse magnetic flux inspection (TFI) tools in general is less than that of axial field tools for general metal loss anomalies.

Additionally, these TFI tools typically require a minimum of two magnetizer assemblies in order to achieve adequate coverage, making it impractical or difficult to incorporate these into an existing axial MFL tool.

For those pipelines that may have extremely narrow metal loss features, or certain classes of seam weld anomalies, standard axial field tools do not provide adequate detection and quantification capabilities. In these cases, for MFL based tools, either the initial or supplemental surveys are performed using a TFI tool. While TFI tools may be capable of detecting extremely narrow anomalies and certain seam weld anomalies, they also detect all of the remaining volumetric metal loss features typically found in pipelines, complicating the process of identifying the targeted anomaly classes.

One of the earliest TFI arrangements is described in U.S. Pat. No. 3,483,466 to Crouch et al. Crouch discloses a pair of electromagnets arranged perpendicular to each other with detectors such as magnetometers or search coils positioned on each side of the magnets. Other than the use of permanent magnets and hall device-type sensors, Crouch's arrangement remains as the basis for most modern implementations. Additionally, some designs involve segmented or individual discrete magnets that, in most cases, retain the transverse or

circumferential field direction. For example, U.S. Pat. No. 3,786,684 to Wiers *et al.* discloses individual magnets arranged in arrays oblique to the pipe axis with the fields of each array perpendicular the others. However, this arrangement limits the field to sections and areas between the poles of each individual magnet. Furthermore, the short pole spacing required for a Wiers-type implementation decreases the length of the magnetic circuit, thereby causing the tool to suffer from velocity effects, and also masks, distorts or degrades data quality at welds, dents, or other anomalies.

Other designs involve elaborate complex geometries, multiple magnetizer sections, and elaborate mechanical arrangements such as helical drives, gears and wheels designed to induce spiral or helical motion of the magnetizer section. For example, U.S. Pat. No. 5,565,633 to Wernicke discloses a mechanically complicated device for use with magnetizer sections having two or more magnetic circuits and a plethora of sensing units. In one embodiment, the magnet blocks are arranged with spirally situated parallel poles. In another embodiment, the magnet blocks are twisted pole pairs displaced axially. Both embodiments require mechanically induced rotation in order to achieve full coverage of the inner pipe surface. Similar to Wernicke, U.S. Pat. No. 6,100,684 to Ramuat discloses a substantially transverse field magnetization arrangement that involves multiple magnetizer sections and a complex arrangement of wheels to induce helical motion of the sections and achieve overlapping or full coverage of the pipe wall. U.S. Pat. No. 7,548,059 to Thompson et al. includes two skids (poles) that incorporate fixed magnets arranged in closely spaced pairs to create a nominally transverse field spiraling around the pipe. This tool—which includes a variety of moving parts such as supporting tendons, pulleys, and springs—requires much added complexity in order to be flexible enough to accommodate bends in the pipeline.

Furthermore, the magnets in this arrangement induce a field between two parallel poles, forming a single closed loop circuit between the poles of the individual discrete magnet blocks.

Similar to Thompson et al., the magnets used in the prior art are described as being blocks, with no reference to a supple or conformable upper surface used for the magnet block. Use of a rigid contact arrangement for the magnetic circuit degrades data quality by introducing air gaps or variable reluctance zones in the magnetic field path at dents or along welds and other upsets that may be present within the pipeline. For certain classes of features, disturbances created in the ambient field mask or otherwise distort the flux leakage signals present because of the features of interest. Any magnetic anomalies existing within dents and weld zones are of greater significance due to their presence within these zones and, as such, represent areas in which data quality is critical.

Additionally, the prior art requires the use of a large number of poles or surfaces in an intimate contact arrangement to the pipe wall surface. This arrangement can result in extremely high frictional forces or resistance to motion being experienced by the magnetizer assembly, thereby inhibiting or preventing its use in applications requiring lower friction.

As already discussed, pipeline operators are currently able to inspect many installed pipelines using the magnetic flux leakage (MFL) technique, primarily for the purpose of identifying metal loss anomalies. However, for certain classes of anomalies, the current axial field magnetizer designs used in the MFL technique make detection and quantification of extremely narrow, crack or crack-like axial features difficult or, in some cases, impossible. To enable detection and quantification of these features, alternative techniques utilizing acoustic (ultrasonic) waves have been studied or employed. These acoustic waves are

typically generated by external piezoelectric transducers or electro-magnetic acoustic transducers (EMAT).

EMAT implementations are usually one of two basic types: Lorentz and magnetostrictive. Both types require an external magnetic bias field to be present. In Lorentz-type EMAT, the magnetic bias field is perpendicular to the pipe wall and interacts with Eddy current-induced paths or strains in the pipe wall. The magnetostrictive-type EMAT uses a magnetic bias field that is in the pipe wall plane, axial or circumferential, and interacts with magnetically induced strains.

It is well known in the nondestructive testing industry that magnetostriction in steel is much more efficient in generating shear horizontal (SH) acoustic waves when the magnetic bias field is at an angle with respect to the sensor coil conductors of the EMAT. This result has been verified by the inventors during initial development of an EMAT sensor array according to the invention disclosed herein. During the study it was discovered that several of the notches machined into test plates were not detectable using an axially oriented magnetic bias field. Rotating the magnetic bias field angle relative to the axis of travel and the EMAT sensor provided an increase of approximately 20 decibels in measured signal. This arrangement produced a much greater signal response compared to the electronic noise, resulting in distinct crack indications above a relatively uniform baseline.

Consequently SH wave applications using EMAT sensor coils that are set at an angle to the magnetic field, are usually superior to applications where the field plane lines are parallel to the sensor coil conductors (see e.g. DE Pat. App. Pub. No. 10/2007/0058043 assigned to Rosen Swiss AG). Detection and quantification of stress corrosion cracking (SCC) is one of the main types of anomalies targeted by this technique. In addition to SCC,

which is typically axially oriented, girth welds, which are circumferentially oriented, have been known to exhibit crack-like features. Therefore, for an EMAT system to be globally effective, a method is needed that is readily adaptable for detection of both axially and circumferentially oriented features.

Prior art in-line inspection tools use annular arrays of permanent magnets to magnetize the pipe in a direction that is parallel to the axis of the pipe. To obtain the beneficial angle between the magnetic bias field and the sensor coils, the sensor coils are rotated toward the pipe axis (see e.g., Canadian Pat. Appl. No. CA 2,592,094 of Alers et al.). The SH waves impinge on the plane of the axially oriented SCC at this same angle. Therefore, SH wave reflections from SCC are detected efficiently only by receiver sensor coils that are positioned lateral to and rotated toward the transmitter coil. Also, the attenuation measurements used for detection of coating disbond use receiver coils that are positioned diagonally to and rotated toward the transmitter coils. These attenuation receiver coils are shifted circumferentially so that they are in-line with the transmitted wave. An appreciable increase in received signal amplitude is an indication a coating disbond.

There is a need for an EMAT tool that provides full coverage of the inner pipe wall surface without the need for mechanically complicated structures and produces a field that may be used with EMAT sensors to detect axially- or circumferentially-oriented volumetric features and coating disbonds.

There is a further need for a MFL tool that provides full coverage of the inner pipe wall surface without the need for mechanically complicated structures; produces a field that detects axially-oriented, circumferentially-oriented and volumetric features; generates similar responses from features regardless of whether the features are axially or circumferentially

oriented; eliminates or reduces velocity effects as well as signal masking, disruptions and distortion at welds, dents and other upsets; navigates pipeline obstructions, bends and reductions; and allows pipeline surveys to be accomplished in a single pass.

Summary of the Invention

A pipeline inspection tool made according to this invention includes at least two pole magnets arranged about an external surface of the tool body and oriented oblique to the central longitudinal axis of the tool body. A sensor array is provided between the opposing edges of the two pole magnets. The sensor array includes a line or set of sensor coils that are oriented at a different angle than the pole magnets relative to the longitudinal axis of the tool body. Therefore, the sensor array is at an angle with respect to the magnetic bias field generated by the pole magnets. The pole magnets and the sensor array may each extend the length of the tool body and have a general helical-shape. Preferably, the sensor coil sets are perpendicular to the longitudinal axis of the tool body but, depending on the type of anomaly to be detected, may be arranged parallel to the longitudinal axis of the tool body.

Each sensor coil set may lie 180° opposite a corresponding sensor coil set, with a portion of the opposing sensor coil sets contained within a common circumferential band of the tool. Sensor coil sets lying on a same side of the tool body are offset from one another, being generally evenly spaced apart and equidistant from the opposing edges of the oblique-oriented pole magnets. Each set of sensor coils includes at least one transmitter coil and at least two opposing pairs of receiver coils. One receiver coil in each pair may be a RD receiver coil and the other receiver coil may be a RA receiver coil. Because the sensor coil sets are rotated relative to the magnetic bias field, the receiver coils are in-line with, and have the same angular orientation as, the transmitter coil. In other words, the receiver coils are

oriented parallel to the transmitter coil and do not need to be shifted diagonally or rotated with respect to the transmitter coil.

The transmitter coil transmits a tone burst or signal that impinges upon the wall of the tubular member being inspected and travels back to the receivers. The receiver coils are spaced relative to the transmitter coil so that the signal transmitted by the transmitter coil does not mask detection of the reflected signal by the receiver coils. Each receiver coil is gated to receive these reflected signals—which may be normalized—within a targeted sampling zone and detect anomalies in the tubular member. The transmitter may then transmit a second signal after the first signal has travelled a predetermined number of times around the circumference of the tubular member. Depending on the orientation of the sensor coil sets relative to the oblique-oriented magnets, the sensor array is capable of detecting wall anomalies in both the axial and circumferential direction.

It is an object of this invention to provide a magnetic flux leakage (MFL) tool that responds to a broad range of anomalies capable of generating magnetic flux leakage signals. Another object of this invention is to provide a MFL tool capable of 360° coverage of the internal pipe wall using a single magnetizer without the need for multiple magnetizer sections, magnetizers, or relative motion between the sensors or sections to achieve detection of nominally axially oriented features. It is another object of this invention to provide a MFL tool with an EMAT array that reduces the probability of missing cracks in the pipe wall and has improved sensitivity to small defects, i.e., up to 20 db increase in signal amplitude. Yet another object of this invention is to provide an EMAT array that requires a substantial decrease in RF pulser power requirements. Still yet another object of this invention is to provide an EMAT array that includes self-calibration of the transmitted signals using the

receiver coils closest to transmitter coils. A further object of this invention is to provide an EMAT array that experiences less interference between transmitters caused by acoustic ring around.

In a further embodiment, a pipeline inspection tool made according to this invention includes a magnetizer assembly having a cylindrical tool body, at least two radial discs, and an even number "n" of pole magnets arranged about an external surface of the cylindrical tool body. Each pole magnet—which preferably has a conformable upper surface, such as a brush-like surface, between the magnet and the internal wall surface of the pipe—extends the length of the cylindrical body located between the two radial discs. The spacing between adjacent pole magnets is about 360°/n, "n" being the number of pole magnets employed. The magnetic flux paths radiate from the magnet poles, diverging in opposite directions and returning to an opposing pole in similar fashion.

The pole magnets are rotated or spiraled about the cylindrical tool body so that a second end of each pole magnet is offset a predetermined amount "α" relative to a first end of that same pole magnet. The amount of rotation α applied to each of the pole magnets produces a magnetic field oblique to the central longitudinal axis of the tool body (and therefore the pipe). The amount of rotation α, which may range from 30° to 150°, is preferably an amount of rotation that is effective for producing a magnetic field that covers 360° of the internal wall surface of a pipe lying opposite the tool body.

A helical-shaped array of magnetic flux sensors may be arranged about the cylindrical tool body and substantially equidistant between adjacent pairs of pole magnets. Preferably, a degree of overlap in the sensor array is provided, with a first end of the array of magnetic flux sensors extending a distance "Δ" past a line containing a second end of the array.

It is an object of this invention to provide a magnetic flux leakage (MFL) tool that responds to a broad range of anomalies capable of generating magnetic flux leakage signals. Another object of this invention is to provide a MFL tool capable of 360° coverage of the internal pipe wall using a single magnetizer without the need for multiple magnetizer sections, magnetizers, or relative motion between the sensors or sections to achieve detection of nominally axially oriented features. Another object of this invention is to provide a MFL tool capable of detecting volumetric-type metal loss features in conjunction with ultrasonic, electro-magnetic acoustic transducer, or magnetostrictive detection methods. Yet another object of this invention is to provide a MFL tool that produces a magnetic field which generates a substantially similar response from axially-oriented or transversely-oriented features as well as generating detectable responses from volumetric-type metal loss features. Still yet another object of this invention is to provide a MFL tool that eliminates or reduces the mechanical motion effects upon flux leakage signals at welds, dents and other upsets. Still another object of this invention is to provide a MFL tool that detects and quantifies the extremely narrow axial classes of anomalies, with the added benefit of doing so in conjunction with an existing axial field magnetizer, providing greater overall accuracy in metal loss anomaly quantification. Another object of this invention is to minimize the number of moving parts and assemblies incorporated into the MFL tool. Still yet another object of this invention is to provide a means for the MFL tool to compress in order to pass by obstructions, bends and reductions in a pipe. A further object of this invention is provide a single tool in which the pipeline survey may be done in a single pass, reducing the amount of effort required by both the pipeline operator and inspection personnel for onsite operations, data handling, data analysis, and final report generation.

Brief Description of the Drawings

FIG. 1A is an isometric view of an axially oriented magnetizer design. The direction of the magnetic field is circumferential or transverse to the longitudinal axis of the pipe.

FIG. 2A is an isometric view of an embodiment of an oblique magnetizer assembly according to this invention that utilizes a spiral magnet pole design. The pole magnets are rotated or spiraled about 30° and include a flexible or conformable upper surface.

FIG. 3A is a view of another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 60°.

FIG. 4A is a view of yet another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 90°.

FIG. 5A is a view of still yet another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 120°.

FIG. 6A is a view of yet another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 150°.

FIG. 7A is an end view of another embodiment of the oblique magnetizer assembly, illustrating the relationship between the two ends of the spiraled or rotated pole magnets. In this example, the pole magnets are rotated about 135°. The conformable upper surface of each pole magnet includes a bristle or brush-type surface.

FIG. 8A illustrates field results from the oblique magnetizer arrangement. The field direction is diagonal, or oblique, to the longitudinal axis of the pipe.

FIG. 9A is a view of an embodiment of the oblique magnetizer assembly that includes a helical-shaped sensor array mounted from one end of the magnetizer to the other, providing

complete coverage of the internal pipe wall surface and incorporating a degree of overlap to accommodate any tool rotation that may take place.

FIG. 10A is a view of the oblique magnetizer assembly of FIG. 8A encased in a pipe section.

FIG. 11A is a view of an inline inspection tool that includes the oblique magnetizer assembly, an axial magnetizer and a deformation sensing section.

FIG. 12A is a schematic illustrating one side of a sensor array that includes two lines or sets of EMAT sensor coils located between two oblique-oriented pole magnets. Each sensor coil set includes two pairs of receiver coils and a transmitter coil located in-between the pairs of receiver coils. The sets are aligned perpendicular to the central longitudinal axis of the inline inspection tool (and, therefore, perpendicular to the central longitudinal axis of the tubular member being inspected) and each coil in the set shares a common centerline with the other coils in the set.

FIG. 13A is a view of one side of a sensor array having the EMAT sensor coil arrangement of FIG. 12A as applied to a 24 inch diameter tubular member.

FIG. 1B is an isometric view of a transversed oriented magnetizer design. The direction of the magnetic field is circumferential or transverse to the longitudinal axis of the pipe.

FIG. 2B is an isometric view of an embodiment of an oblique magnetizer assembly according to this invention that utilizes a spiral magnet pole design. The pole magnets are rotated or spiraled about 30° and include a flexible or conformable upper surface.

FIG. 3B is a view of another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 60°.

FIG. 4B is a view of yet another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 90°.

FIG. 5B is a view of still yet another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 120°.

FIG. 6B is a view of yet another embodiment of the oblique magnetizer assembly in which the pole magnets are rotated about 150°.

FIG. 7B is an end view of another embodiment of the oblique magnetizer assembly of illustrating the relationship between the two ends of the spiraled or rotated pole magnets. In this example, the pole magnets are rotated about 135°. The conformable upper surface of each pole magnet includes a bristle or brush-type surface.

FIG. 8B illustrates field results from the oblique magnetizer arrangement. The field direction is diagonal, or oblique, to the longitudinal axis of the pipe.

FIG. 9B is a view of an embodiment of the oblique magnetizer assembly that includes a helical-shaped sensor array mounted from one end of the magnetizer to the other, providing complete coverage of the internal pipe wall surface and incorporating a degree of overlap to accommodate any tool rotation that may take place.

FIG. 10B is a view of the oblique magnetizer assembly of FIG. 8B encased in a pipe section.

FIG. 11B is a view of an inline inspection tool that includes the oblique magnetizer assembly, an axial magnetizer and a deformation sensing section.

Detailed Description of the Preferred Embodiments

Preferred embodiments of a magnetic flux leakage (MFL) tool made according to this invention will now be described by making reference to the drawings and the following elements illustrated in the drawings:

10	In-line inspection tool	65	Second end of 61
20	MFL tool / oblique magnetizer	67	Longitudinal centerline of 61
21	Cylindrical tool body	69	Conformable upper surface
23	First end of 21	71	Brushes
25	Second end of 21	80	Magnetic field
27	Longitudinal axis of 21	81	Magnetic flux path of field 80
31	Radial disc	90	Sensor array
40	Magnetic circuit	91	First end of 90
41	Pole magnet	93	Second end of 90
43	First end of 41	94	Sensor coil line or set of 95, 97 & 98
45	Second end of 41	95	Transmitter coil
47	Longitudinal centerline of 41	96	Shear horizontal wave generated by 95
49	Conformable upper surface	97	RD receiver coil
51	Brushes	98	RA receiver coil
61	Pole magnet	99	Central axis of sensor coil set 94
63	First end of 61	100	Axial magnetizer
		110	Deformation sensing section
310	In-line inspection tool	351	Brushes
320	MFL tool / oblique magnetizer	361	Pole magnet
321	Cylindrical tool body	363	First end of 61
323	First end of 21	365	Second end of 61
325	Second end of 21	367	Longitudinal centerline of 61
327	Longitudinal axis of 21	369	Conformable upper surface
331	Radial disc	371	Brushes
340	Magnetic circuit	380	Magnetic field
341	Pole magnet	381	Magnetic flux path of field 380
343	First end of 341	390	Sensor array
345	Second end of 341	391	First end of 390
347	Longitudinal centerline of 341	393	Second end of 390
349	Conformable upper surface	400	Axial magnetizer
		410	Deformation sensing section

Figures 1A through 13A show one embodiment of the invention. Referring first to FIG. 1A, a north pole magnet 41 and a south pole magnet 61 are arranged about 180°

opposite one another on a cylindrical tool body 21 so that the respective longitudinal centerline 47, 67 of each pole magnet 41, 61 is parallel to the longitudinal centerline 27 of the cylindrical tool body 21 (and therefore parallel to a central longitudinal axis of the pipe being inspected). Although pole magnets 41, 61 differ from prior art implementations in that, for example, each magnet 41, 61 extends along the entire length of the cylindrical body 21, their axial orientation as illustrated here is typical of prior art implementations. Arranged in this way, pole magnets 41, 61 generate a circumferential or transverse magnetic field relative to the pipe wall—as illustrated by magnetic flux paths 81—and multiple magnetizer sections are required to provide complete coverage of the internal wall surface of the pipe.

Referring now to FIGS. 2A to 6A, an oblique magnetizer assembly 20 according to this invention includes a magnetic circuit 40 that has two spiraled pole magnets 41, 61 arranged about 180° opposite one another on cylindrical tool body 21. Each pole magnet 41, 61 extends between a first end 23 and second end 25 of the cylindrical tool body 21. Additional pairs of spiraled pole magnets 41, 61 may also be employed, with each spiraled pole magnet 41 or 61 extending between the ends 23, 25 of cylindrical tool body 21 and spaced 360°/n from its adjacent and opposite pole magnet 61, 41 ("n" being an equal to the number of pole magnets 41, 61 employed). The pole magnets 41, 61 preferably have a flexible or conformable upper surface 49, 69, respectively, that helps reduce friction forces and minimize velocity effects as the oblique magnetizer assembly 20 travels through the interior of a pipe. The conformable upper surface 49, 69 also allows the magnetizer assembly 20 to compress a sufficient amount in order to pass by internal obstructions, bends, and reductions in the pipe that might otherwise damage the magnetizer assembly 20 or slow or prevent its passage.

The rotation amount of the pole magnets 41, 61 depends on the amount of rotation required to achieve full coverage of the internal pipe wall surface. Going through the sequence from FIG. 2A to FIG. 6A, the pole magnets 41, 61 are each rotated or spiraled in incremental amounts, for a nominal rotation of about 150 degrees (as illustrated in FIG. 6A). When rotated, the second end 45, 65 of the pole magnet 41, 61 is offset by a predetermined angle or amount α relative to its respective first end 43, 63 (see FIG. 7A). Because of this rotation amount α, the respective longitudinal centerline 47, 67 of each spiraled pole magnet 41, 61 is non-parallel to the central longitudinal axis 27 of the cylindrical tool body 21. The rotation of pole magnets 41, 61 also helps induce a sufficient amount of rotation of magnetizer assembly 20 as it travels through the interior of the pipe.

FIG. 8A illustrates the magnetic field 80 generated from a prototype of oblique magnetizer assembly 20, which was configured similar to the magnetizer assembly 20 shown in the rotation sequence of FIGS. 2A to 6A. Unlike prior art in-line inspection tools, the direction of magnetic field 80 is diagonal or oblique to the pipe axis rather than circumferential or transverse, with magnetic flux paths 81 emanating from the poles 41, 61 and traveling in opposite directions to reach a corresponding pole 61, 41. The magnetic flux lines 81 generated by each pole magnet 41, 61 are guided to the path of least resistance: into the pipe wall and toward the adjacent pole magnet 61, 41. The angle of the magnetic field 80 is generally perpendicular to the flux lines 81 formed by the magnetic poles 41, 61 and generally parallel to a line forming the shortest distance between the magnet poles 41, 61. The direction of magnetic field 80 within the extents of poles 41, 61 may range from 30 to 60 degrees relative to the pipe axis.

Referring now to FIGS. 9A & 10A oblique magnetizer assembly 20 may include a helical-shaped sensor array 90 located substantially equidistant between rotated pole magnets 41, 61 and arranged to provide complete coverage of the internal wall surface W of pipe P and accommodate any rotation of magnetizer assembly 20 that may take place. The individual sensors in sensor array 90 may be of a kind well-known in the art for detecting magnetic flux leakage signals. Sensor array 90 preferably extends between the first end 23 and second end 25 of cylindrical body 21 (and therefore between the respective ends 43, 45 and 63, 65 of pole magnets 41, 61) and incorporates a degree of overlap Δ between a first end 91 and second end 93 of sensor array 90. The conformable upper surfaces 49, 69 of the pole magnets 41, 61 (see e.g. FIG. 6A) may be in the form of brushes 51, 71. Radial discs 31A & B help propel and center magnetizer assembly 20 as it moves forward in pipe P under differential pressure.

The final configuration of oblique magnetizer assembly 20 may include any current combination of data sets, including but not limited to deformation, high level axial MFL, internal/external discrimination, inertial data for mapping, and low level or residual MFL. In one preferred embodiment of an inline inspection tool 10 incorporating oblique magnetizer assembly 20, the tool 10 includes an axial magnetizer 100 and a deformation sensing section 110 (see FIG. 11A).

Referring now to FIGS. 12A & 13A, sensor array 90 includes electro-magnetic acoustic transducers (EMAT) sensor coils 95, 97 & 98 located between the opposing edges 42, 62 of the oblique-oriented permanent pole magnets 41, 61. The sensor coils 95, 97 & 98 are preferably arranged in sensor coil lines or sets 94a-e as defined by a respective sensor coil set central axis 99a–e. Each central axis 99a–e is generally parallel to the other axes 99a–e

and oriented at a predetermined angle γ relative to the central longitudinal axis 27 of cylindrical tool body 21. A substantially identical set of sensor coil sets (not shown) to sensor coil sets 94a–e is arranged on the opposing external surface of cylindrical tool body 21, about 180° opposite sensor coil sets 94a–e.

The oblique-oriented pole magnets 41, 61 are generally at an angle β relative to central longitudinal axis 27, with angle β being different than angle γ. Because the flux lines 81 generated by pole magnets 41, 61 are generally perpendicular to the edges 42, 62 of the pole magnets 41, 61, magnetic field 80 is rotated at an angle ε relative to the central longitudinal axis 21 and, therefore, is at an angle with respect to sensor coil sets 94a-e. In a preferred embodiment, angle γ is about 90°, angle β is about 45°, and angle ε is about 45°.

Arranging the sensor coil sets 94a–e perpendicular to the central longitudinal axis 27 of cylindrical tool body 21 (and therefore perpendicular to the pipe axis) allows sensor array 90 to detect features in both the axial and circumferential directions. Transmitter coils 95 generate SH waves 96 that travel circumferentially around the pipe and impinge at a normal angle (perpendicular) to axially oriented cracks. Arranging the sensor coil sets 94a–e parallel to the central longitudinal axis 27 of the cylindrical tool body 21 (and therefore parallel to the pipe axis) allows sensor array 90 to detect features in the circumferential direction. Shear horizontal waves 96 are transmitted along the pipe wall in the axial direction so that reflections from transverse cracks, such as cracks in girth welds, are detected. Unlike the orientation of receivers in prior art EMAT tools, receiver coils 97, 98 do not have to be shifted diagonally with respect to, or rotated toward, the transmitter coil 95 in order to gain

the benefits of having magnetic field 80 rotated with respect to the EMAT sensor coils 95, 97 & 98.

Sensor coils 95, 97 & 98 may be mounted on a suitable mechanism such as a spring loaded pads (not shown) that keep the coils 95, 97 & 98 in close proximity to the inside diameter of the pipe. The transmitter coils 95 induce SH guided waves 96 in two circumferential directions around the pipe. The receiver coils 97 detect reflections from stress corrosion cracks (SCC) and serve as the calibration receivers. Receiver coils 98 detect the SH guided waves 96 that propagate from the transmitter coils 95 in the circumferential direction. The characteristic features of these detected signals, such as amplitude and time of arrival, can be used to detect features such as coating disbond, corrosion and SCC.

The receiver coils 97, 98 are placed at a predetermined distance from transmitter coil 95 so that signal responses are detected by receiver coils 97, 98 but not affected adversely by the initial electronic excitation pulse. Each transmitter coil 95 in a set 94a–e is grouped with two receiver coils 97, 98 on each side. Sensor array 90 preferably includes the requisite number of transmitter coils 95 and receiver coils 97, 98 in order to provide overlapping coverage of SCC and coating disbond detection. In one preferred embodiment, each of two sensor arrays 90—arranged opposite one another and for use in a 24-inch diameter pipe—included five transmitter coils 95 and 20 total receiver coils 97, 98.

Each transmitter coil 95 when fired causes SH guided waves 96 to propagate to both to the left and to the right of the coil 95 and around the circumference of the pipe. The receiver coils 97, 98 closest to the active transmitter coil 95 are first sampled in time (gated) to receive the outgoing waves 96 and then gated at a longer predetermined time delay, preferably on the order of 50 and 90 microseconds for a 24-inch diameter pipe, to detect

reflections from SCC. These reflections are from targeted sampling zones "Z" located between the RD receiver coils 97 and a predetermined distance "D" past the RA receiver coils 98 so as to maximize coverage and minimize interference. The reflection signals are normalized, i.e., divided by the outgoing signals detected in the RD receivers 97 to provide continuous calibration of the signal reflections.

By way of example, considering a 24-inch pipe and a target axial sample spacing of 6 mm (0.24 in.), a pulse rate of 390 Hz will yield an axial resolution of 5.1 mm (0.20 in.). This pulse rate allows the SH wave 96 to travel approximately 4.25 times around the pipe circumference before the second pulse or tone burst is fired. Consequently, the remnants of the first pulse are between the receiver coils 97, 98 and therefore have no affect on the receiver coils 97, 98 located on the opposite side of tool body 21 within that circumferential ring at the sampling time interval (gate).

The SH waves 96 are still within the receiver gates during the third tone burst, after the wave 96 has traveled about 8.5 times around the pipe. Using an attenuation factor of 0.8 in 2 feet of travel (a factor determined from lab experiments), a tone burst transmitted at 100 percent full scale has an amplitude of less than 0.3 percent when it arrives at the receiver coils 97, 98 located on the opposite side of the cylindrical tool body 21. This amount of noise is usually negligible compared to other sources of noise, e.g., thermal electronic noise, which can be as much as 3 percent of full scale.

Coating disbond is detected in the targeted sampling zones Z between RD receiver coils 97 and RA receiver coils 98 which are located in-line with the transmitter coils 95. Coating disbond detection may be accomplished by computing the ratio of the gated receiver

signals. Ratios that are above a set threshold indicate a lack of coating or disbond on the pipe in a particular zone 99.

In studies conducted by the inventors, a sensor array 90 made according to this invention has shown the following benefits over the prior art:

- improved sensitivity to small defects, i.e., up to 20 db increase in signal amplitude;
- substantial decrease in RF pulser power requirements;
- full circumferential inspection coverage, reducing the probability of missing cracks;
- self-calibration of the transmitted signals using the receiver coils closest to transmitter coils; and
- less interference between transmitter coils caused by acoustic ring around.

Additional configurations are possible, depending upon the pipe diameter, with differing numbers of pole magnets 41, 61, sensor coils 95, 97 & 98 and sensor arrays 90. For circumferential detection, for example, the sensor array 90 would be rotated at an oblique angle γ relative to the pipe axis, still being located within the angular magnetic biasing field 80. In addition to SCC and crack-like features, these configurations could respond to features such as coating disbonds and metal loss. The resulting system may also be used as an EMAT-only system or combined with any of the various other technologies available in in-line inspection tools, including but not limited to MFL, Deformation, Caliper, and Mapping.

Figures 1B through 11B show a second embodiment of the invention. Referring first to FIG. 1B, a north pole magnet 341 and a south pole magnet 361 are arranged about 180°

opposite one another on a cylindrical tool body 321 so that the respective longitudinal centerline 347, 367 of each pole magnet 341, 361 is parallel to the longitudinal centerline 327 of the cylindrical tool body 321 (and therefore parallel to a central longitudinal axis of the pipe being inspected). Although pole magnets 341, 361 differ from prior art implementations in that, for example, each magnet 341, 361 extends along the entire length of the cylindrical body 321, their axial orientation as illustrated here is typical of prior art implementations. Arranged in this way, pole magnets 341, 361 generate a circumferential or transverse magnetic field relative to the pipe wall—as illustrated by magnetic flux paths 381—and multiple magnetizer sections are required to provide complete coverage of the internal wall surface of the pipe.

Referring now to FIGS. 2B to 6B, an oblique magnetizer assembly 320 according to this invention includes a magnetic circuit 340 that has two spiraled pole magnets 341, 361 arranged about 180° opposite one another on cylindrical tool body 321. Each pole magnet 341, 361 extends between a first end 323 and second end 325 of the cylindrical tool body 321. Additional pairs of spiraled pole magnets 341, 361 may also be employed, with each spiraled pole magnet 341 or 361 extending between the ends 323, 325 of cylindrical tool body 321 and spaced 360°/n from its adjacent and opposite pole magnet 361, 341 ("n" being an equal to the number of pole magnets 341, 361 employed). The pole magnets 341, 361 preferably have a flexible or conformable upper surface 349, 369, respectively, that helps reduce friction forces and minimize velocity effects as the oblique magnetizer assembly 320 travels through the interior of a pipe. The conformable upper surface 349, 369 also allows the magnetizer assembly 320 to compress a sufficient amount in order to pass by internal

obstructions, bends, and reductions in the pipe that might otherwise damage the magnetizer assembly 320 or slow or prevent its passage.

The rotation amount of the pole magnets 341, 361 depends on the amount of rotation required to achieve full coverage of the internal pipe wall surface. Going through the sequence from FIG. 2B to FIG. 6B, the pole magnets 341, 361 are each rotated or spiraled in incremental amounts, for a nominal rotation of about 150 degrees (as illustrated in FIG. 6B). When rotated, the second end 345, 365 of the pole magnet 341, 361 is offset by a predetermined angle or amount α relative to its respective first end 343, 363 (see FIG. 7B). Because of this rotation amount α, the respective longitudinal centerline 347, 367 of each spiraled pole magnet 341, 361 is non-parallel to the central longitudinal axis 327 of the cylindrical tool body 321. The rotation of pole magnets 341, 361 also helps induce a sufficient amount of rotation of magnetizer assembly 320 as it travels through the interior of the pipe.

FIG. 8B illustrates the magnetic field 380 generated from a prototype of oblique magnetizer assembly 320, which was configured similar to the magnetizer assembly 320 shown in the rotation sequence of FIGS. 2B to 6B. Unlike prior art in-line inspection tools, the direction of magnetic field 380 is diagonal or oblique to the pipe axis rather than circumferential or transverse, with magnetic flux paths 381 emanating from the poles 341, 361 and traveling in opposite directions to reach a corresponding pole 361, 341. The magnetic flux lines 381 generated by each pole magnet 341, 361 are guided to the path of least resistance: into the pipe wall and toward the adjacent pole magnet 361, 341. The angle of the magnetic field 380 is generally perpendicular to the flux lines 381 formed by the magnetic poles 341, 361 and generally parallel to a line forming the shortest distance

between the magnet poles 341, 361. The direction of magnetic field 380 within the extents of poles 341, 361 may range from 330 to 360 degrees relative to the pipe axis.

Referring now to FIGS. 9B & 10B oblique magnetizer assembly 320 may include a helical-shaped sensor array 390 located substantially equidistant between rotated pole magnets 341, 361 and arranged to provide complete coverage of the internal wall surface W of pipe P and accommodate any rotation of magnetizer assembly 320 that may take place. The individual sensors in sensor array 390 may be of a kind well-known in the art for detecting magnetic flux leakage signals. Sensor array 390 preferably extends between the first end 323 and second end 325 of cylindrical body 321 (and therefore between the respective ends 343, 345 and 363, 365 of pole magnets 341, 361) and incorporates a degree of overlap Δ between a first end 391 and second end 393 of sensor array 390. The conformable upper surfaces 349, 369 of the pole magnets 341, 361 (see e.g. FIG. 6B) may be in the form of brushes 351, 371. Radial discs 331A & B help propel and center magnetizer assembly 320 as it moves forward in pipe P under differential pressure.

The final configuration of oblique magnetizer assembly 320 may include any current combination of data sets, including but not limited to deformation, high level axial MFL, internal/external discrimination, inertial data for mapping, and low level or residual MFL. In one preferred embodiment of an inline inspection tool 310 incorporating oblique magnetizer assembly 320, the tool 310 includes an axial magnetizer 400 and a deformation sensing section 410 (see FIG. 11B).

While an EMAT tool and a MFL tool that includes an oblique magnetizer and helical sensor array has been described with a certain degree of particularity, many changes may be made in the details of construction and the arrangement of components. An EMAT tool

according to this disclosure, therefore, is limited only by the scope of the attached claims, including the full range of equivalency to which each element thereof is entitled.

WHAT IS CLAIMED IS:

1. A pipeline inspection tool comprising:

a magnetizer assembly having a cylindrical tool body, and at least two pole magnets having opposite polarity;

each pole magnet being spaced apart from the other pole magnet and spiraled less than half a turn about said cylindrical tool body to create a single oblique magnetic field around said cylindrical tool body;

wherein no induced rotation of the magnetizer assembly is required to provide 360° coverage by the single oblique magnetic field of an internal pipeline wall.

2. A pipeline inspection tool according to Claim 1 further comprising the amount of α spiraling being in a range of 30° to 150°.

3. A pipeline inspection tool according to Claim 1 further comprising at least one pole magnet having a flexible upper surface.

4. A pipeline inspection tool according to Claim 3 further comprising said flexible upper surface being brushes.

5. A pipeline inspection tool according to Claim 1 further comprising an array of magnetic flux sensors arranged about said cylindrical tool body and between said two pole magnets.

6. A pipeline inspection tool according to Claim 5 further comprising said array of magnetic flux sensors being arranged in a helix-shaped arrangement.

7. A pipeline inspection tool according to Claim 6 further comprising a first end of said array of magnetic flux sensors extending a distance "Δ" past a line containing a second end of said array.

8. A pipeline inspection tool according to Claim 1 further comprising the single spiral magnetic field having a direction in a range of 30° to 60° relative to a central longitudinal axis of said cylindrical tool body.

9. A pipeline inspection tool comprising:

a magnetizer assembly having a cylindrical tool body and a single pair of pole magnets having opposite polarity,

each pole magnet in said single pair of pole magnets being spaced apart from one another and spiraled about said cylindrical tool body to provide a single magnetic circuit which creates a magnetic flux flowing in helical directions around said cylindrical tool body.

10. A pipeline inspection tool according to Claim 9 wherein said cylindrical body is arranged to move in a linear fashion in a direction of product flow within a pipeline.

11. A pipeline inspection tool according to Claim 9 wherein each pole magnet is spiraled in a range of 30° to 150°.

12. A pipeline inspection tool comprising

a first end,

a second end opposite the first end,

and a single primary sensor section positioned between the first and second ends, the primary sensor section comprising

a substantially rigid frame;

at least one magnet pair, each magnet in the pair spiraling about the substantially rigid frame less than half a turn and being a continuous magnetic pole of opposite polarity from the other magnet in the magnet pair;

at least one sensor,

the at least one magnet pair producing a first magnetic field having an orientation, the orientation being directed obliquely with respect to each of the circumferential and axial directions;

wherein the pipeline inspection tool when in use in a pipeline generates one or more oblique magnetic fields each having the orientation, the one or more oblique magnetic fields comprising the first magnetic field and all other magnetic fields that emanate from the pipeline inspection tool and are oriented obliquely with respect to each of the

13. A pipeline inspection method comprising:

identifying a pipeline defining a circumferential direction and an axial direction and containing an in-line inspection tool comprising:

a first end,

a second end opposite the first end,

and a primary magnetic flux leakage sensor section positioned between the first and second ends,

the primary magnetic flux leakage sensor section comprising

at least one magnet pair spiraled about the tool body less than half a turn; and

at least one sensor arranged between the at least one magnet pair,

the at least one magnet pair producing a first magnetic field having an orientation, the orientation being directed obliquely with respect to each of the circumferential and axial directions;

producing relative motion between the at least one magnet pair and the pipeline, the relative motion comprising substantially exclusively translation in the axial direction of the at least one magnet pair with respect to the pipeline;

generating, by the in-line inspection tool during the producing, one or more oblique magnetic fields each having the orientation, the one or more oblique magnetic fields comprising the first magnetic field and all other magnetic fields that emanate from the in-line inspection tool and are oriented obliquely with

respect to each of the circumferential and axial directions, the spacing of the at least one magnet pair and the translation in the axial direction during the producing being effective for the at least one sensor to detect nominally axially oriented features of the pipeline without requiring induced rotation of the in-line inspection tool; and

collecting, by the at least one sensor during the generating, data characterizing one or more physical characteristics of the pipeline.

14. A pipeline inspection method comprising:

identifying a pipeline defining a circumferential direction and an axial direction and containing an in-line inspection tool comprising:

a first end,

a second end opposite the first end, and

a primary sensor section, the primary sensor section comprising a magnet dipole and at least one sensor, the magnet dipole formed by spaced-apart opposite pole magnets and producing a first magnetic field having an orientation, the orientation being directed obliquely with respect to each of the circumferential and axial directions;

producing relative motion between the magnet dipole and the pipeline, the relative motion comprising substantially exclusively translation in the axial direction of the magnet dipole with respect to the pipeline;

generating, by in-line inspection tool during the producing, one or more oblique magnetic fields each having the orientation, the one or more oblique magnetic fields comprising the first magnetic field and all other magnetic fields that emanate from the in-line inspection tool and are oriented obliquely with respect to each of the circumferential and axial directions, the spacing of the magnet dipole and the translation in the axial direction during the producing being effective for the at least one sensor to detect nominally axially oriented features of the pipeline without requiring induced rotation of the in-line inspection tool; and

collecting, by the at least one sensor during the generating, data characterizing one or more physical characteristics of the pipeline.

15. A pipeline inspection method comprising:

identifying a pipeline defining a circumferential direction and an axial direction and containing an in-line inspection tool comprising

a first end,

a second end opposite the first end, and

a primary sensor section, the primary sensor section comprising

a substantially rigid frame,

at least two continuous magnetic poles each spiraling less than half a turn about the substantially rigid frame, and

at least one sensor,

the at least two continuous magnetic poles producing a first magnetic field having an orientation, the orientation being directed obliquely with respect to each of the circumferential and axial directions;

producing relative motion between the at least two continuous magnetic poles and the pipeline, the relative motion comprising substantially exclusively translation in the axial direction of the at least two continuous magnetic poles with respect to the pipeline;

generating, by the in-line inspection tool during the producing, one or more oblique magnetic fields each having the orientation, the one or more oblique magnetic fields comprising the first magnetic field and all other magnetic fields that emanate from the in-line inspection tool and are oriented obliquely with respect to each of the circumferential and axial directions, the translation in the axial direction during the producing being effective for the at least one sensor to detect nominally axially oriented features of the pipeline without requiring induced rotation of the in-line inspection tool; and

collecting, by the at least one sensor during the generating, data characterizing one or more physical characteristics of the pipeline.

16. The method of claim 15 wherein the primary sensor section further comprises at least one brush contact extending radially outward from each continuous magnetic pole of the at least two continuous magnetic poles.

17. A pipeline inspection tool according to claim 1 wherein each pole magnet spans the distance between a forward and a rearward radial disc of the cylindrical tool body.

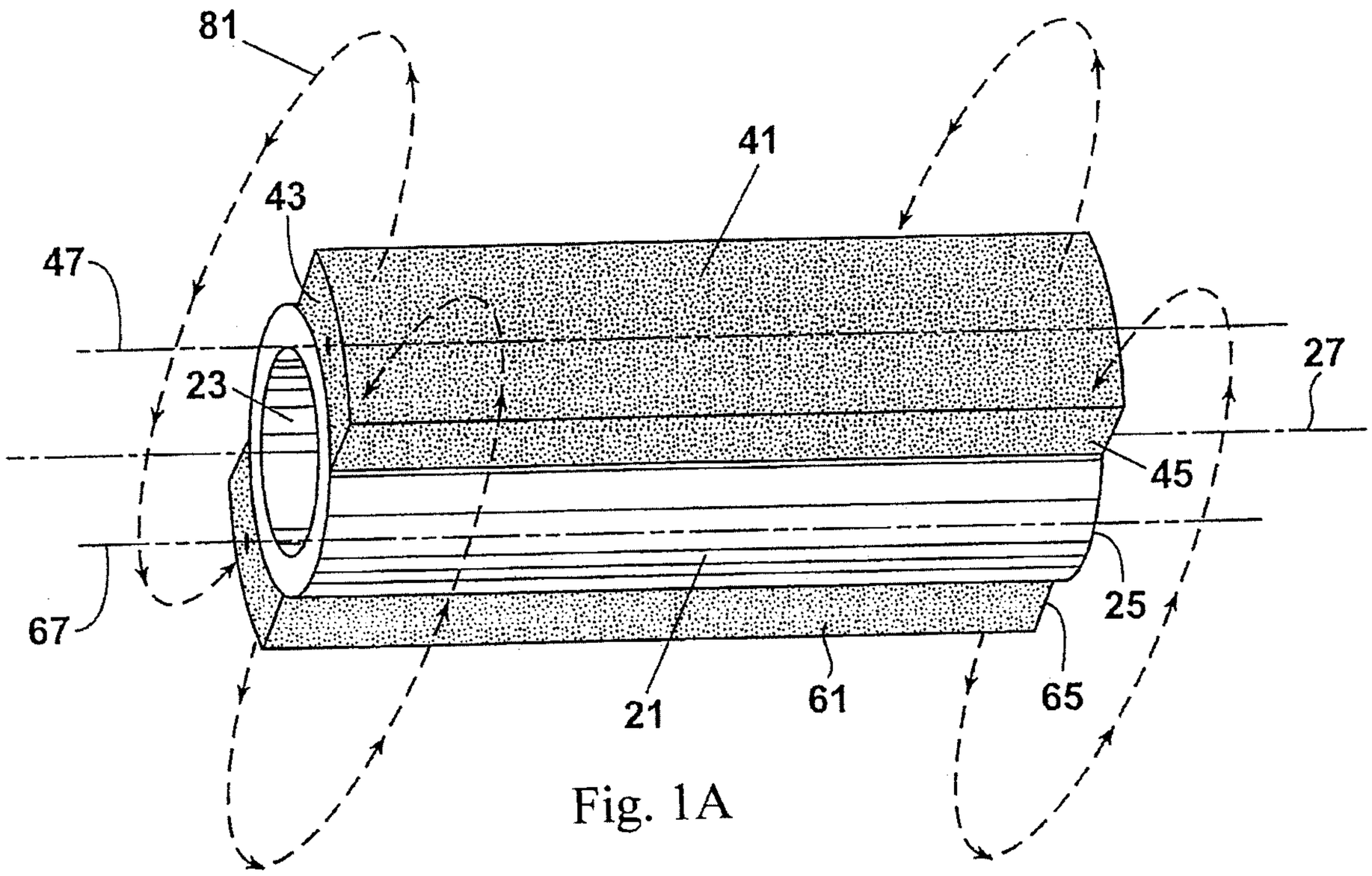

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Fig. 1A

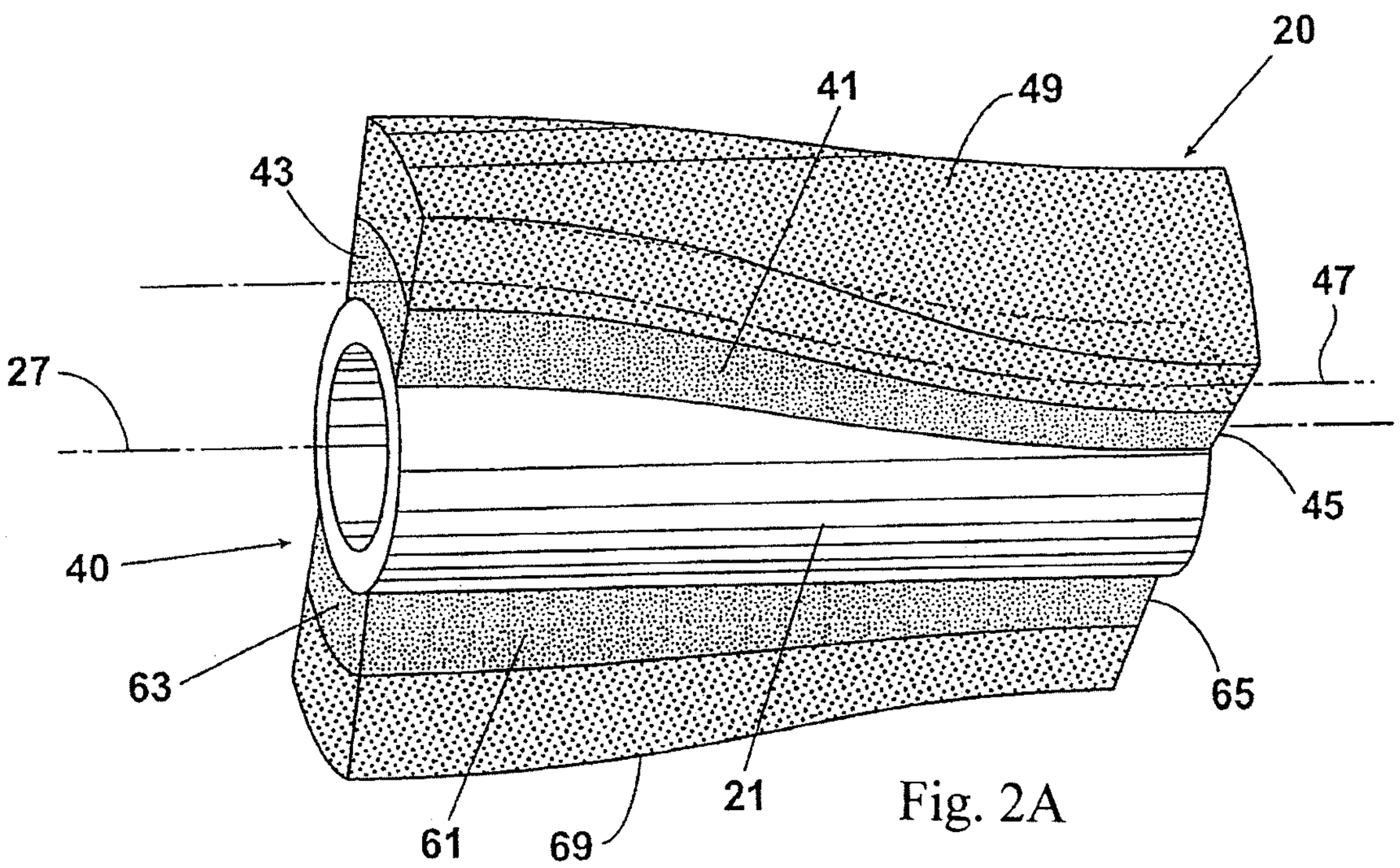

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Fig. 2A

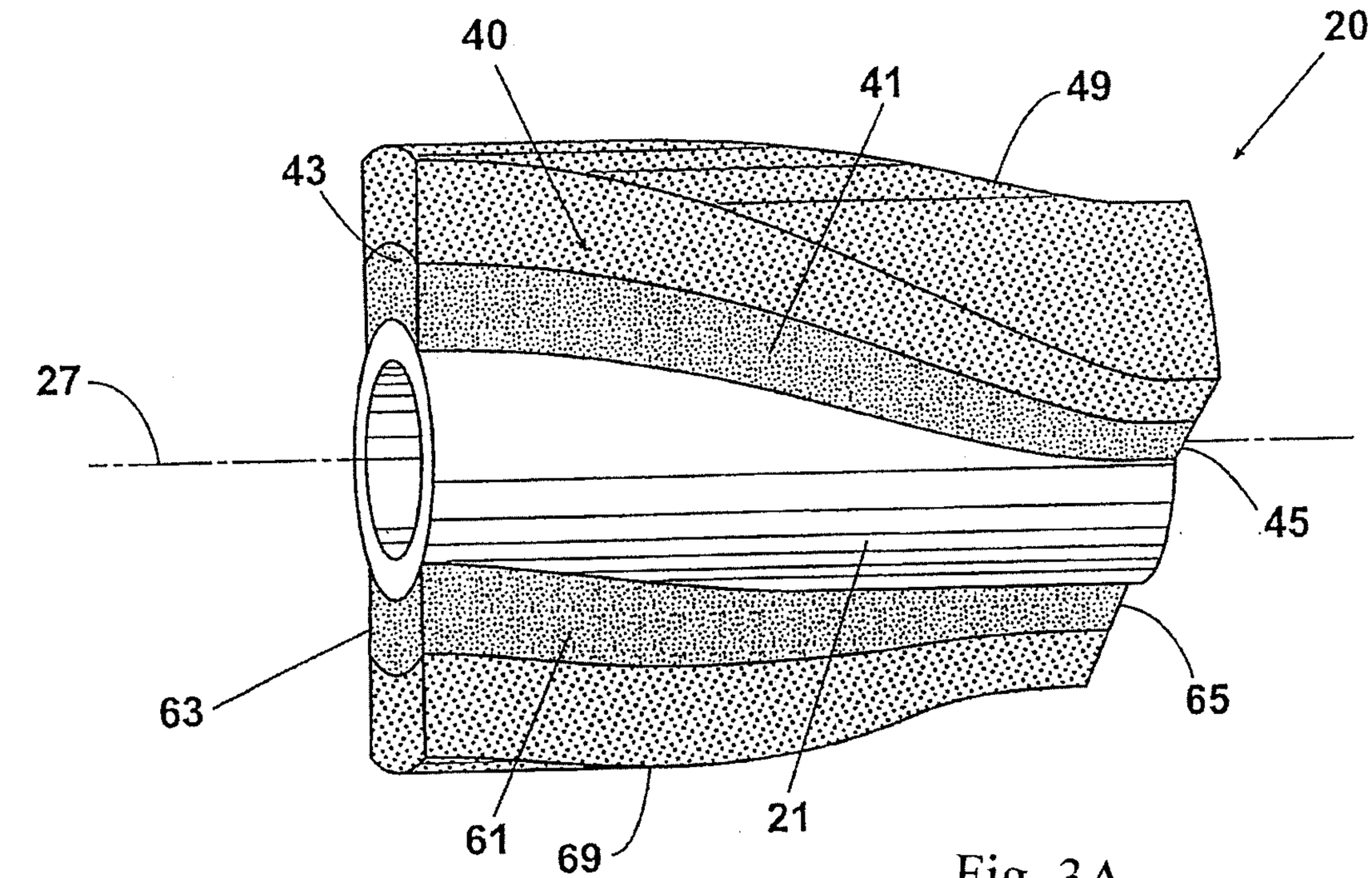


Fig. 3A

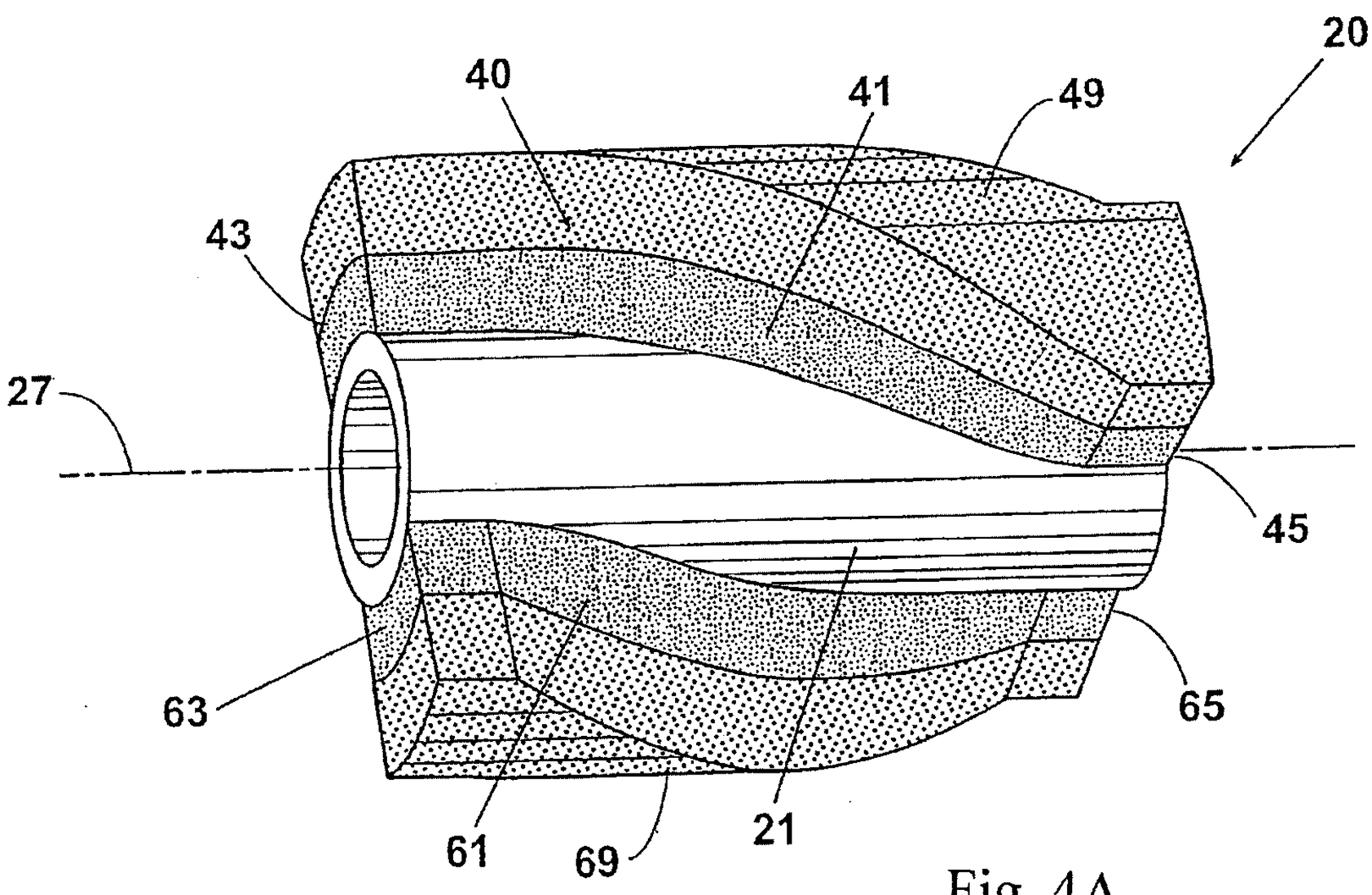


Fig. 4A

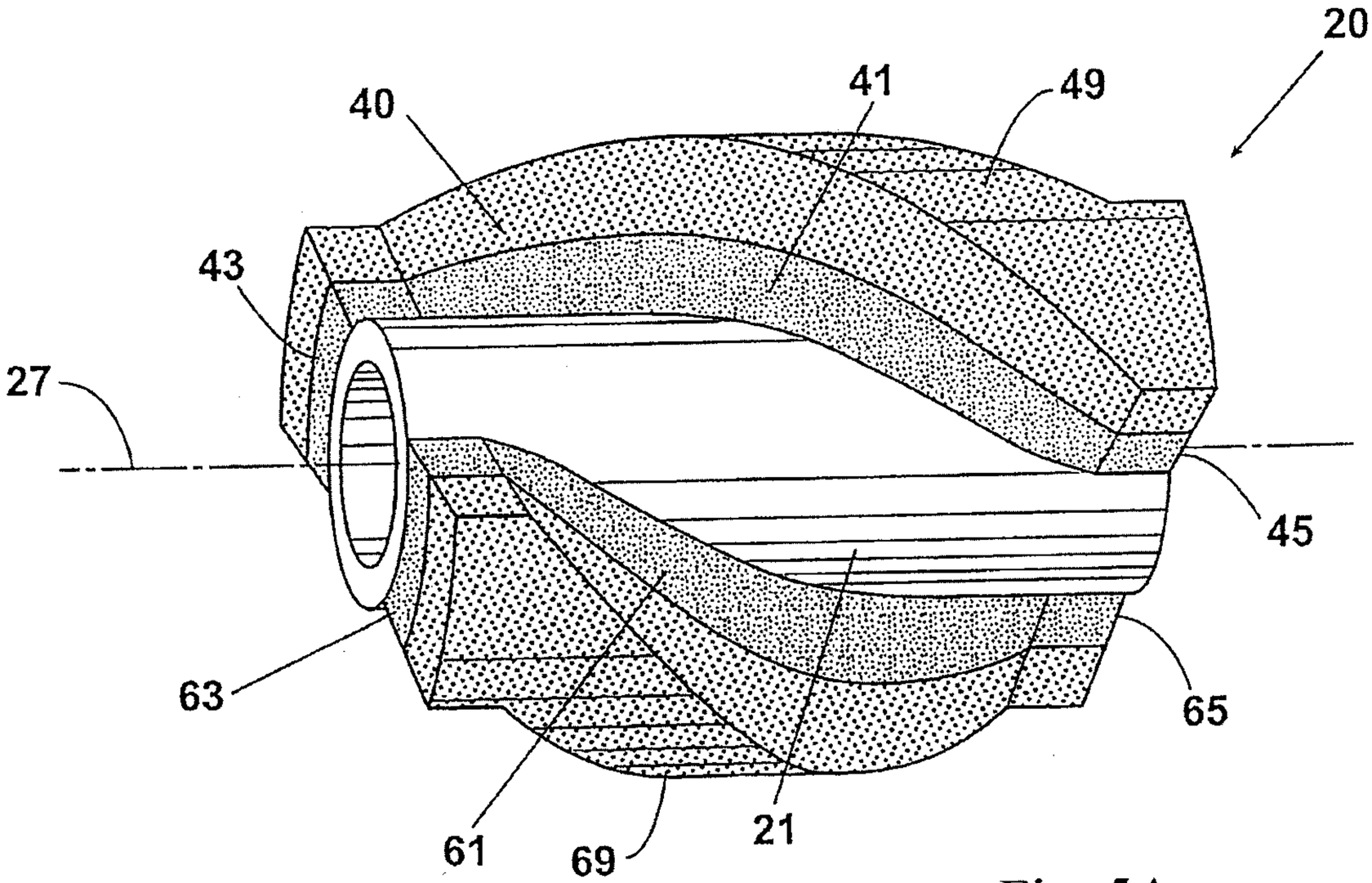


Fig. 5A

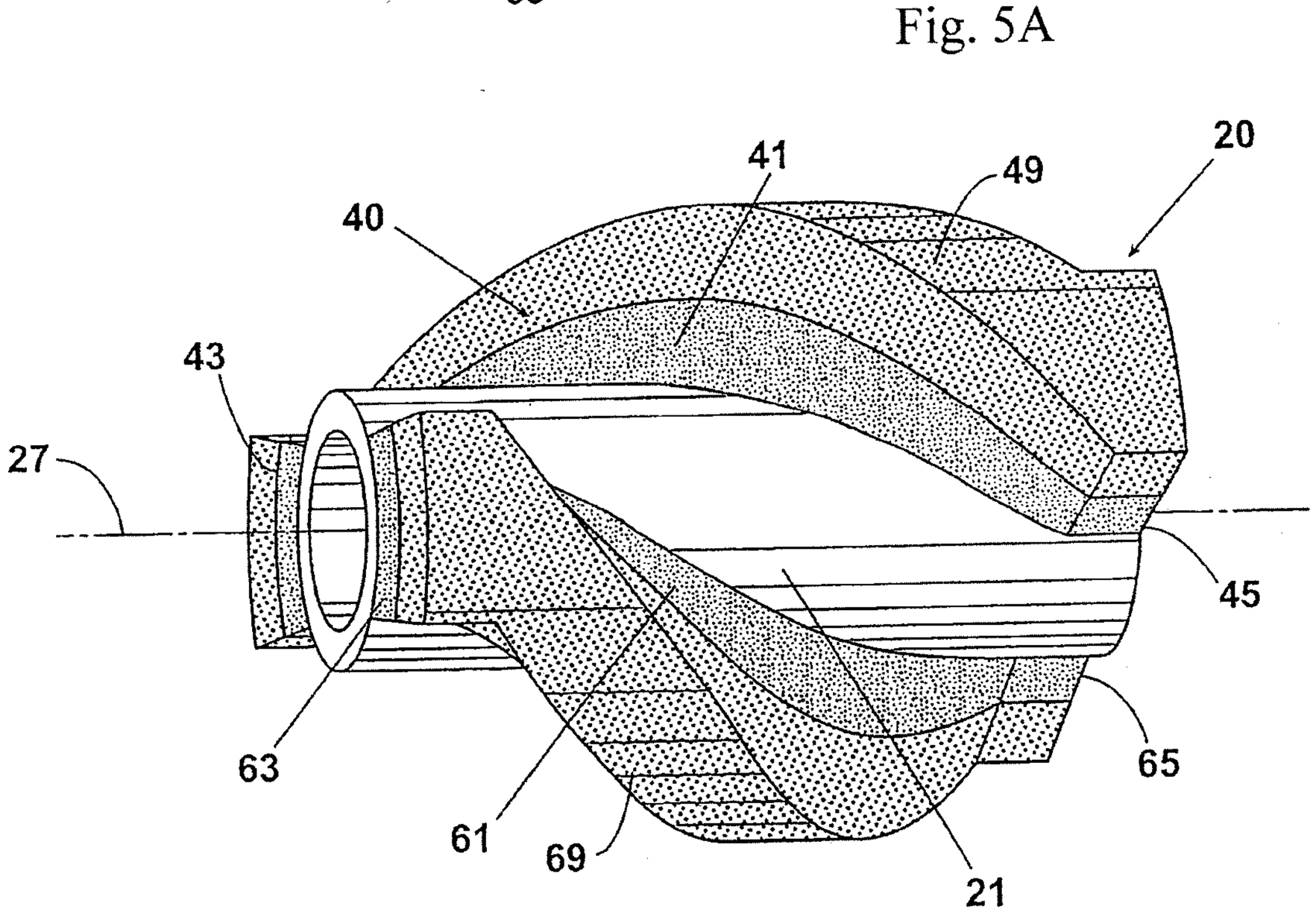


Fig. 6A

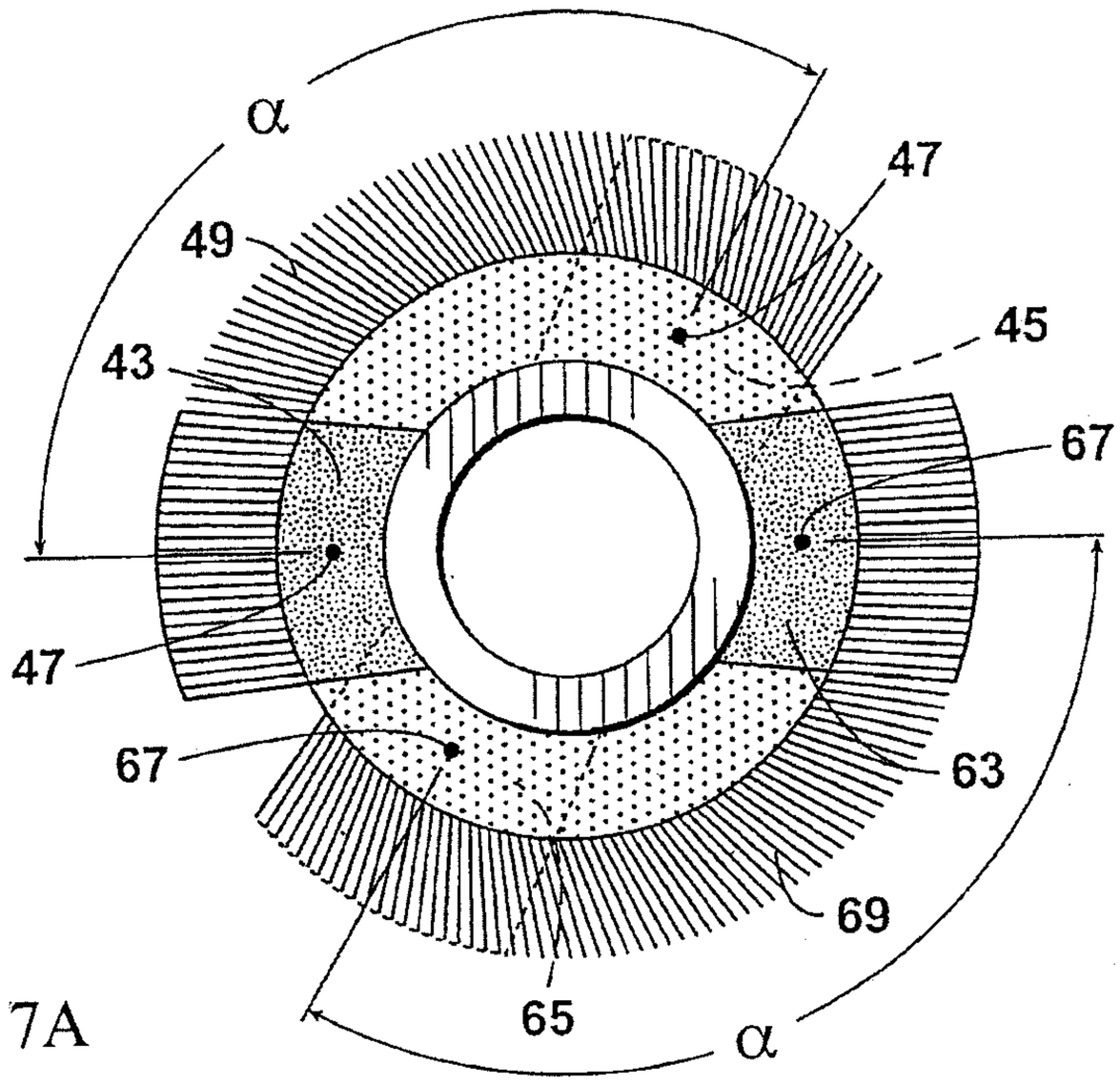


Fig. 7A

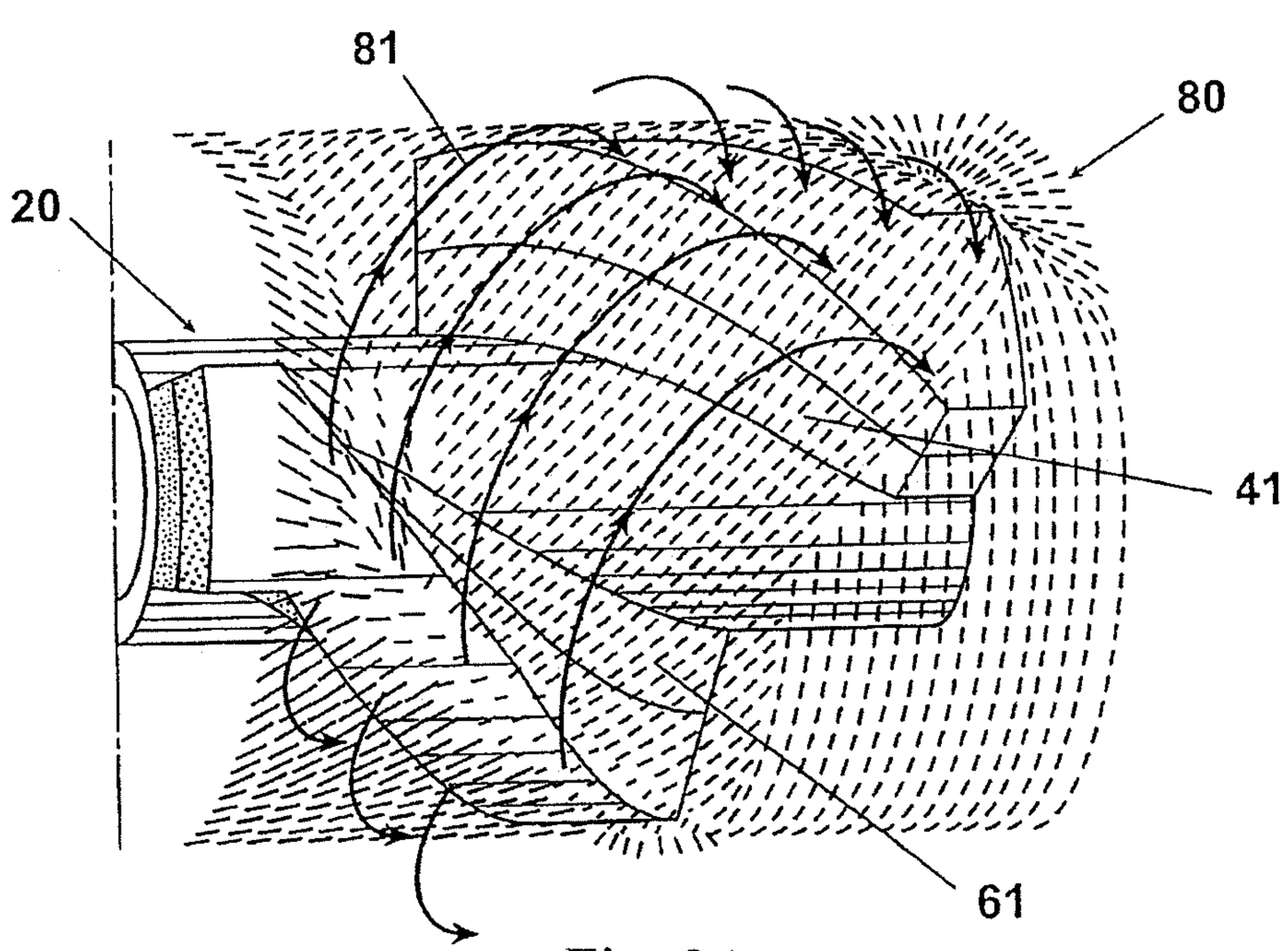


Fig. 8A

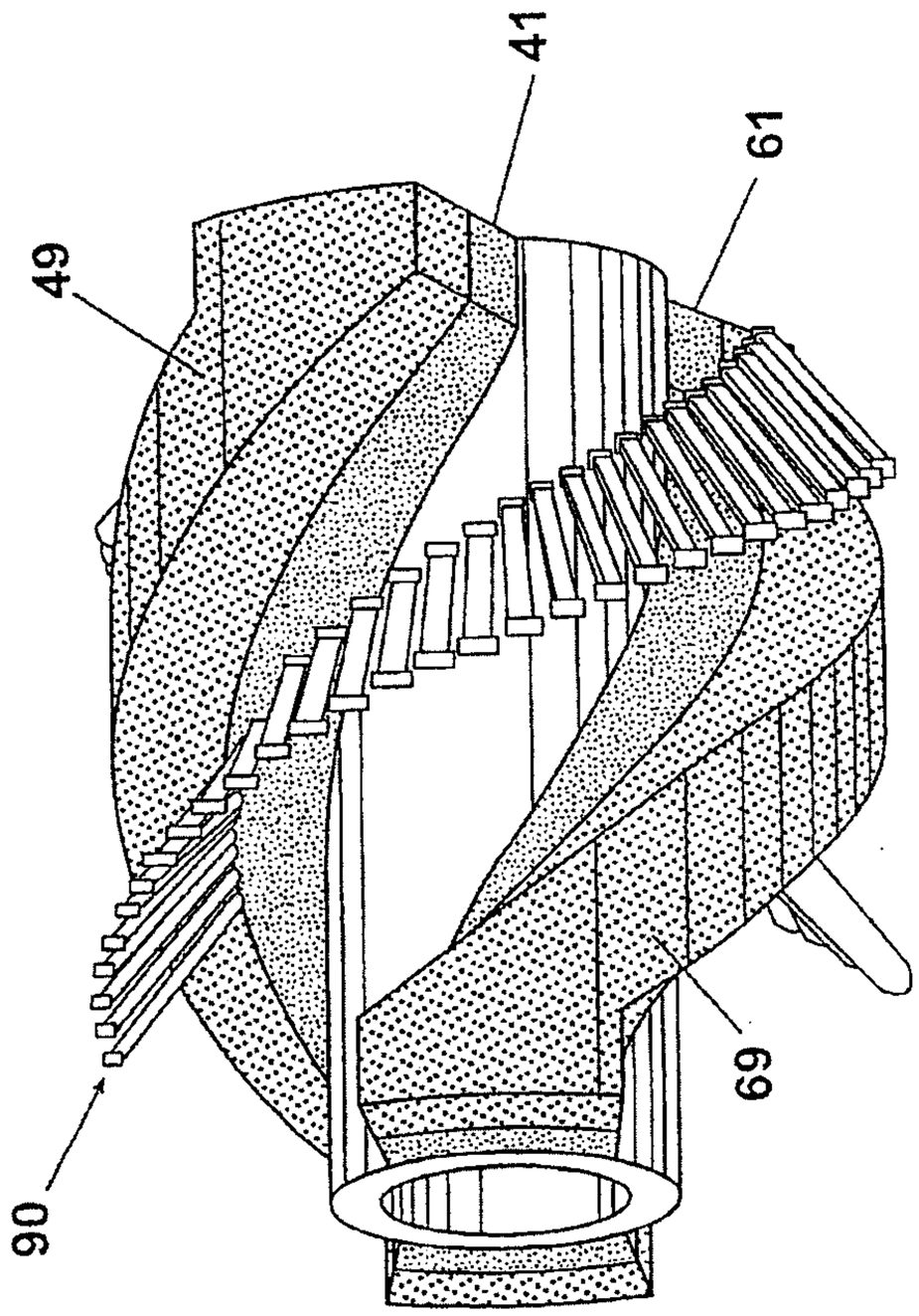


Fig. 9A

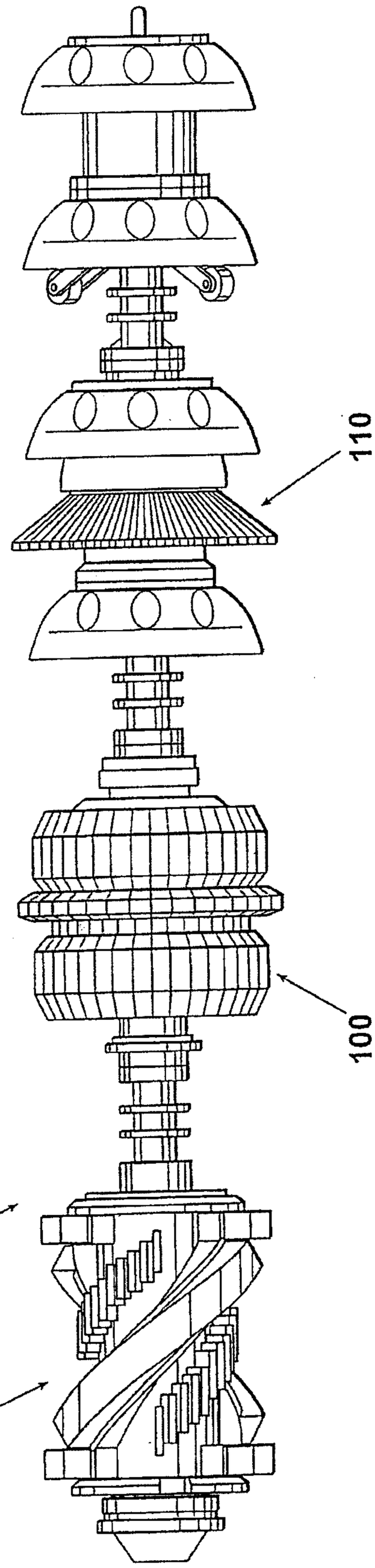


Fig. 11A

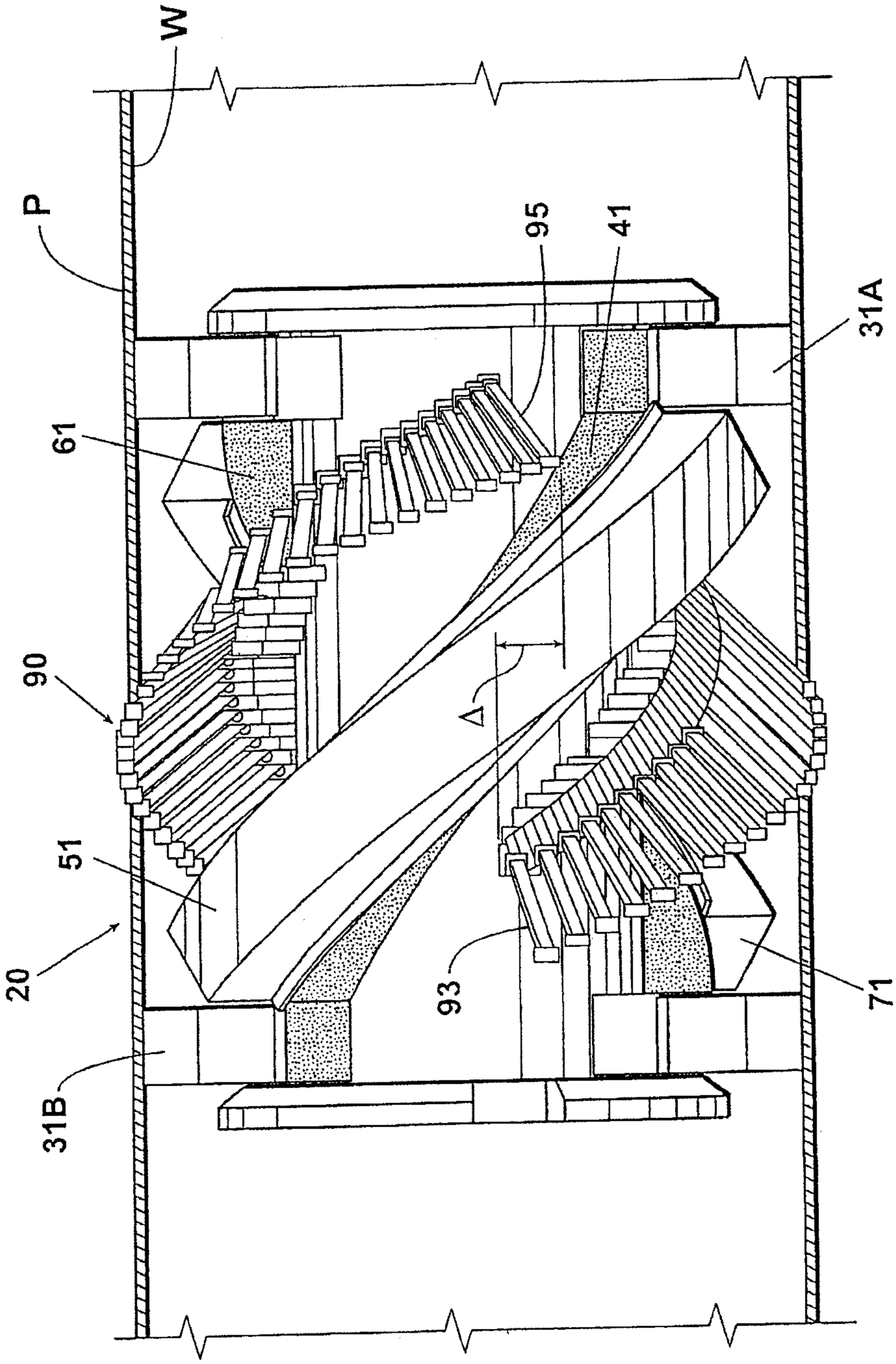


Fig. 10A

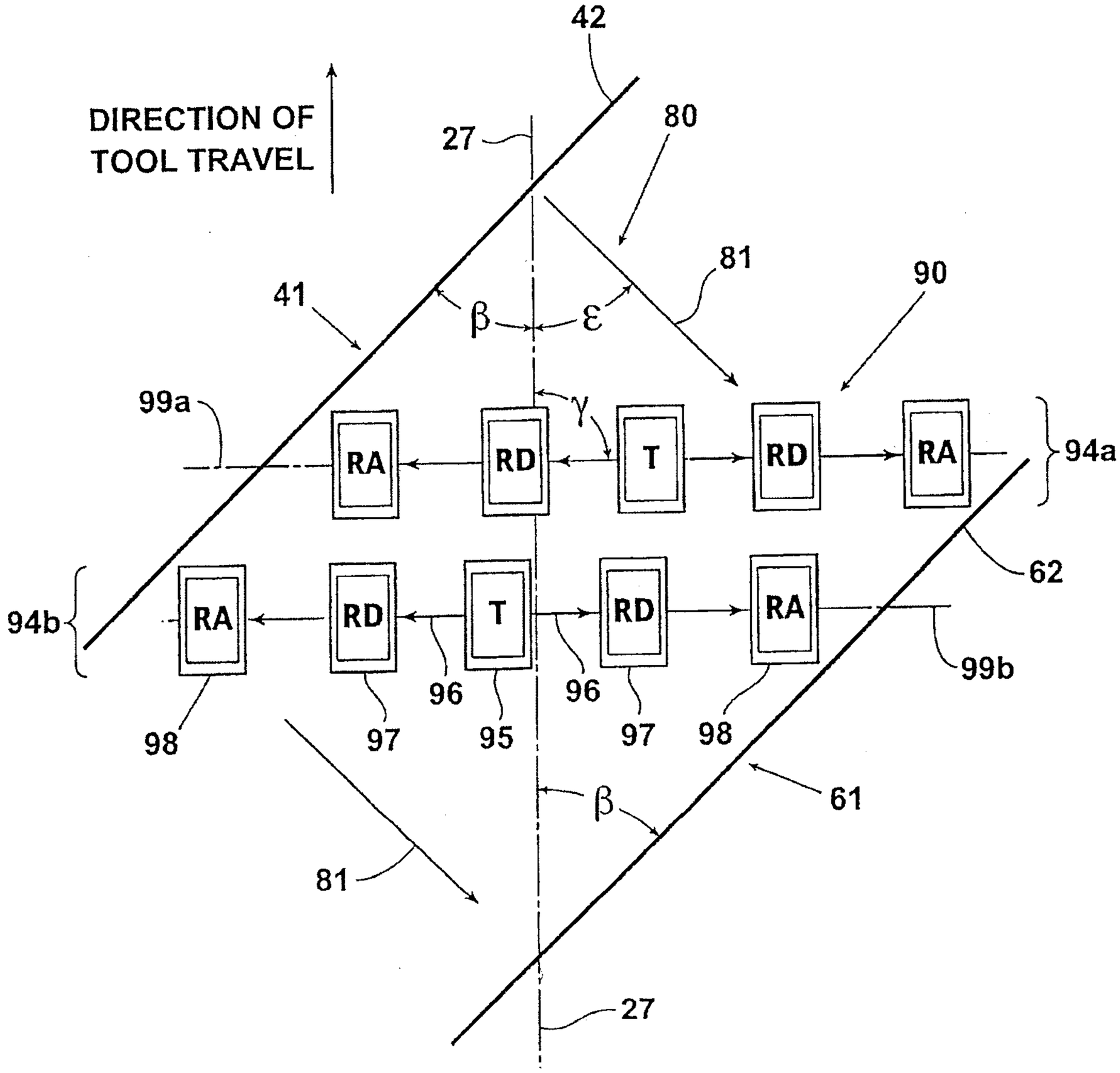

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Fig. 12A

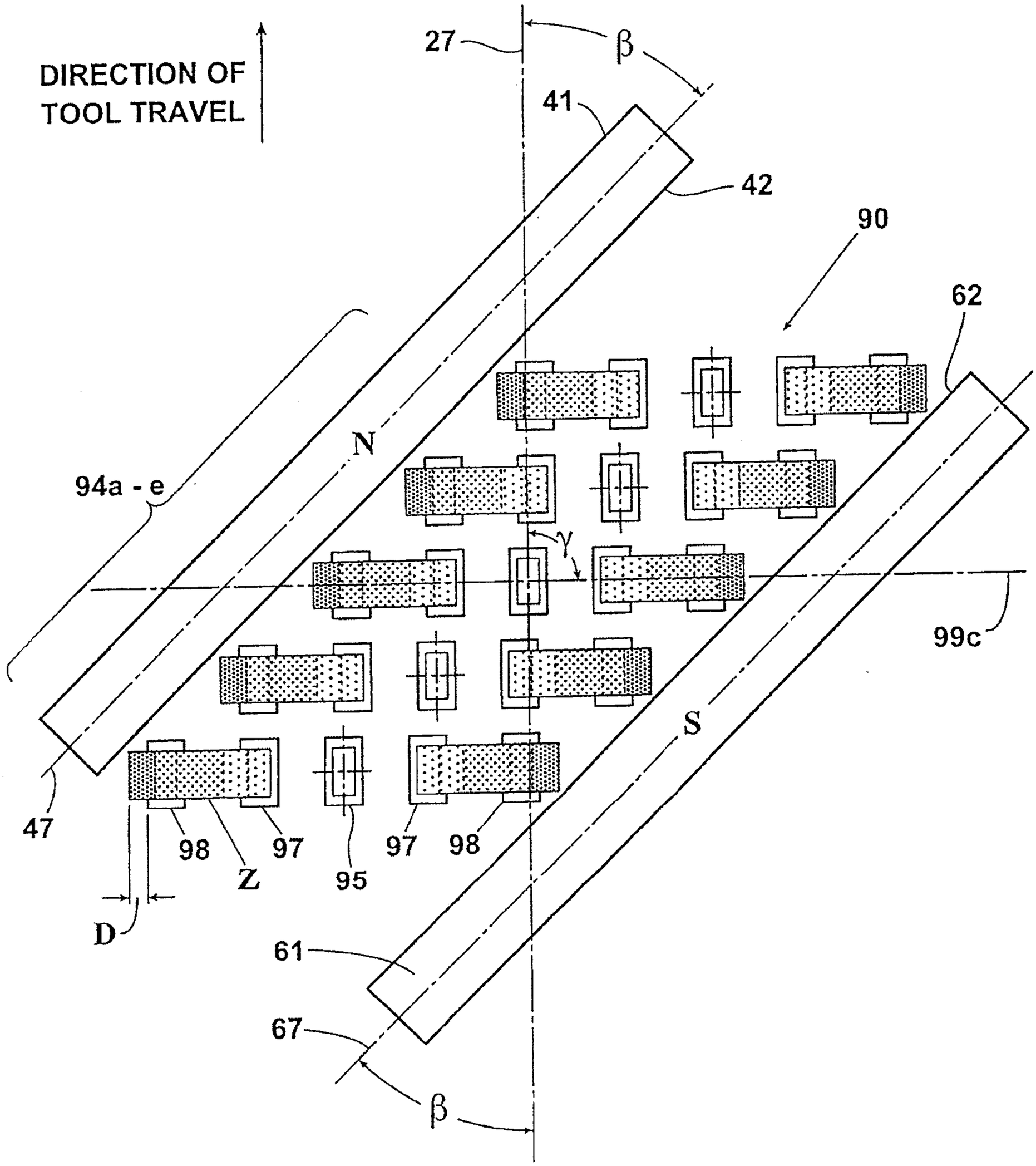

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Fig. 13A

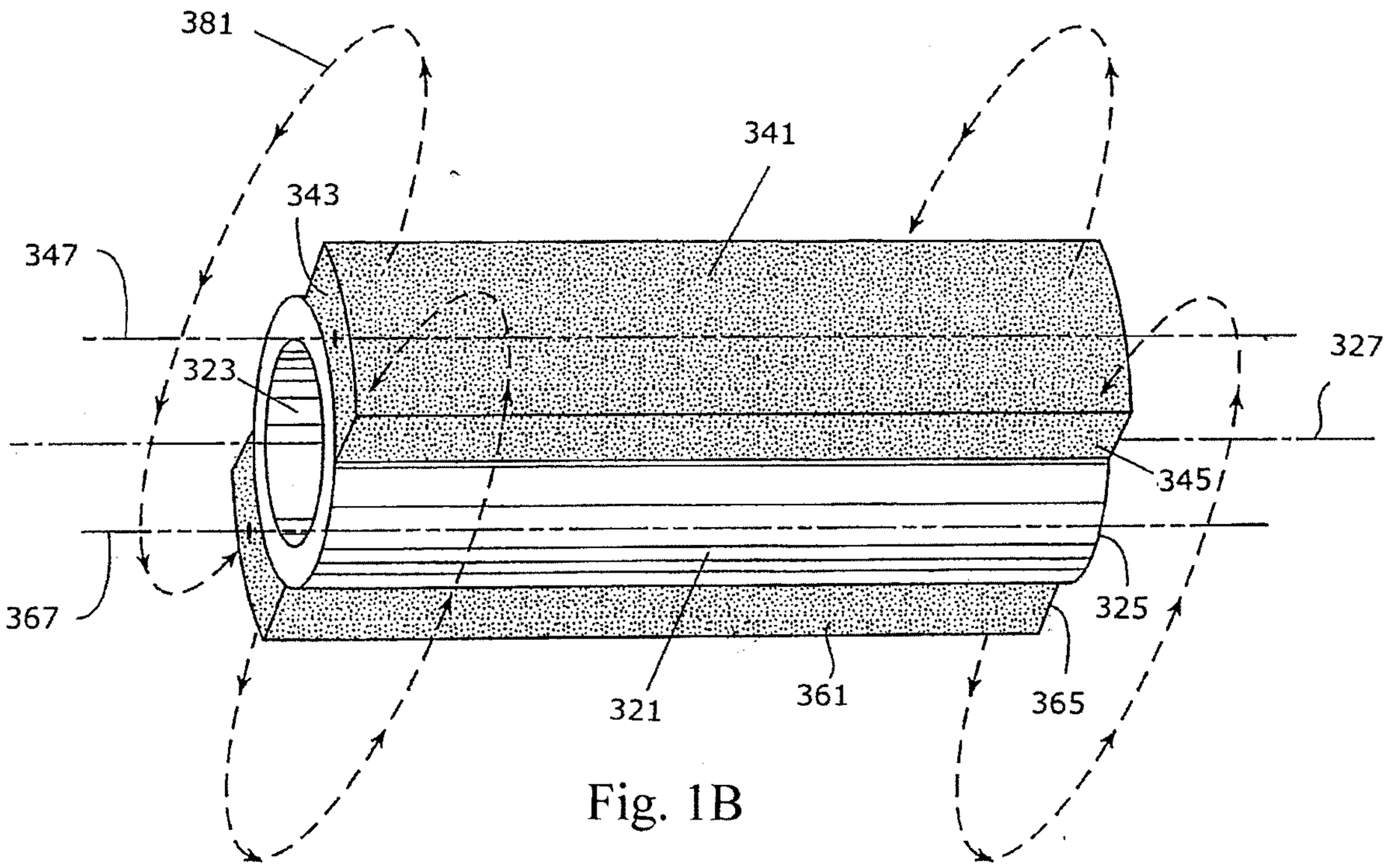

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Fig. 1B

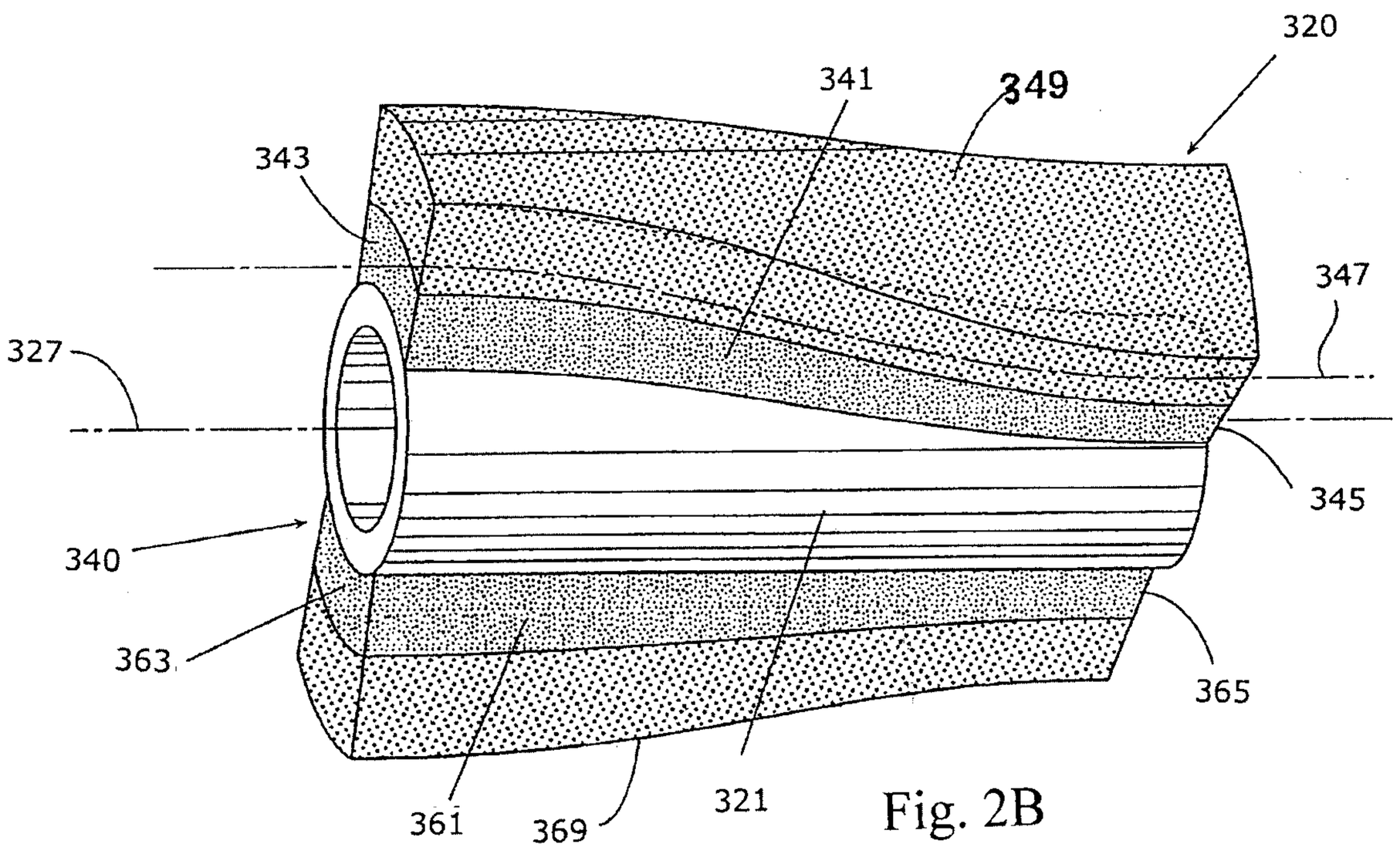

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Fig. 2B

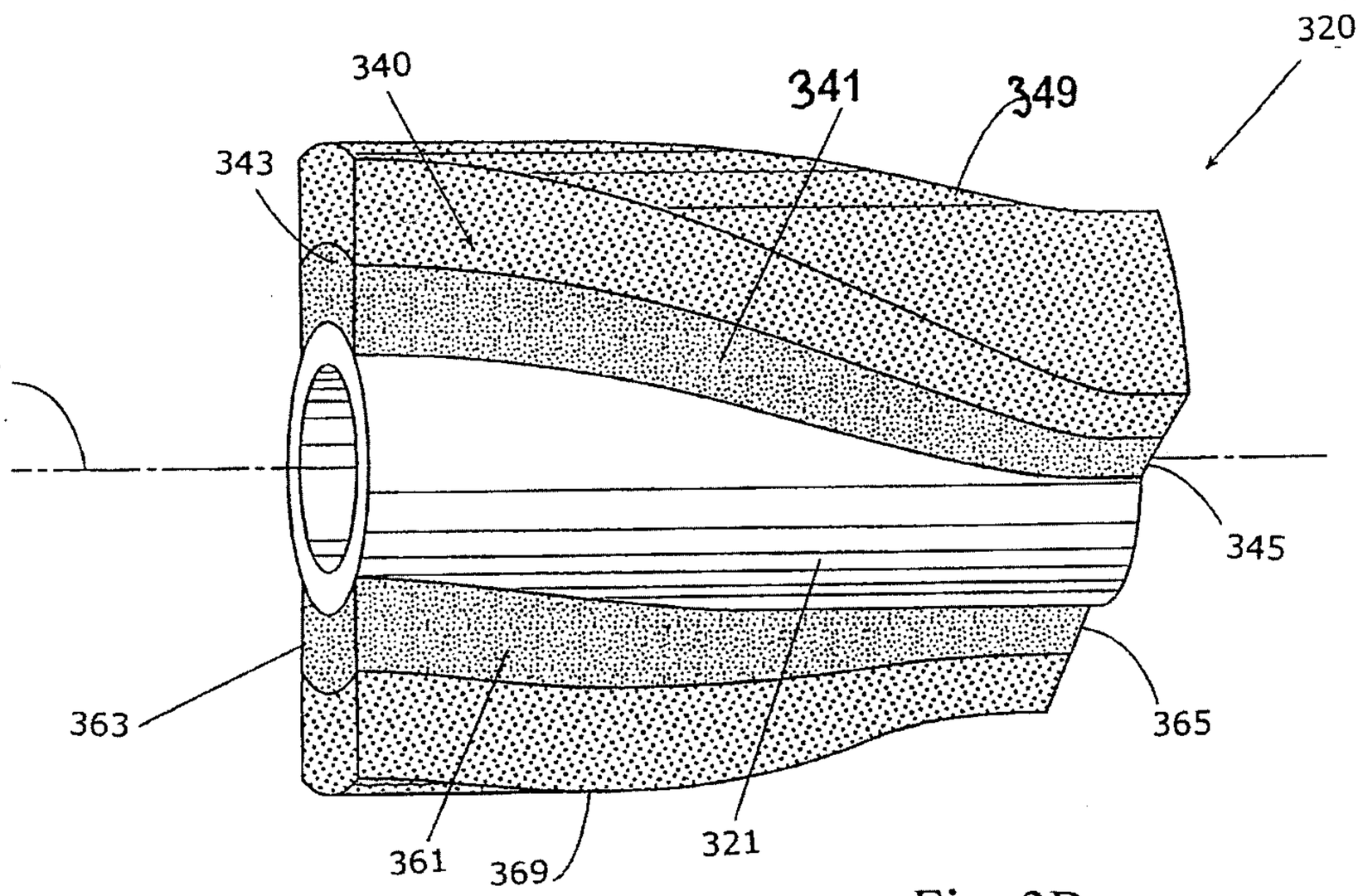

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Fig. 3B

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Fig. 4B

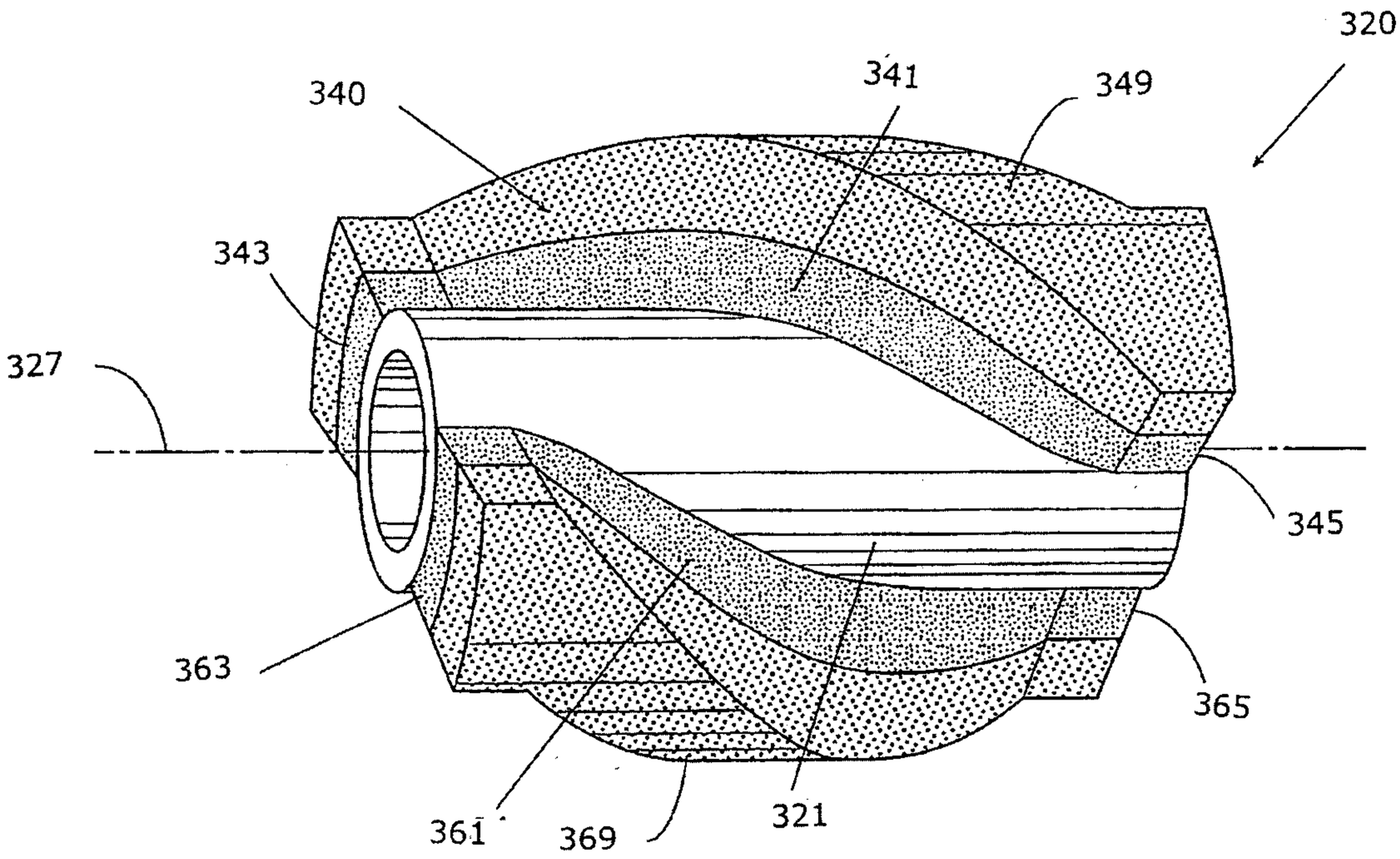

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Fig. 5B

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Fig. 6B

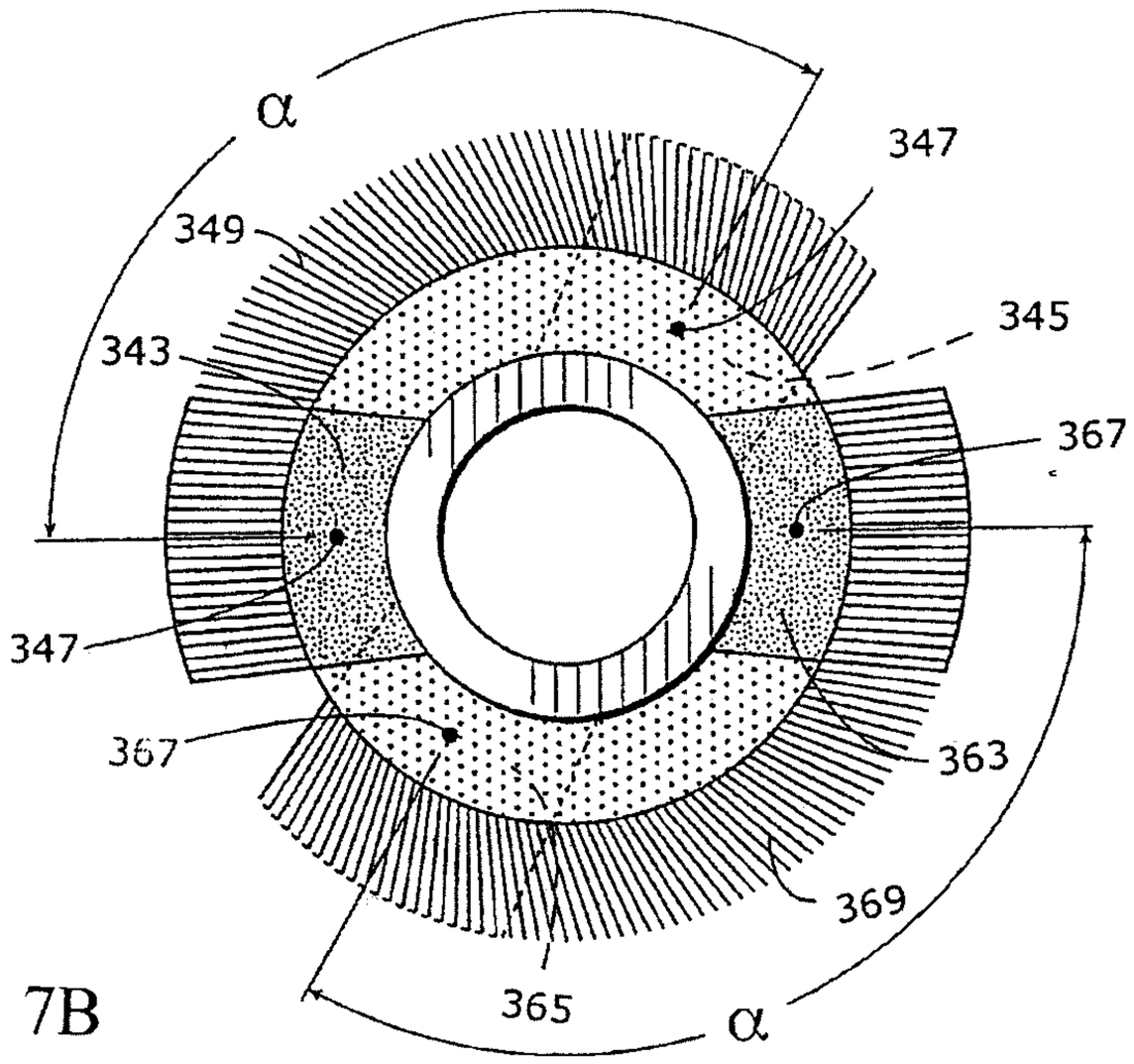


Fig. 7B

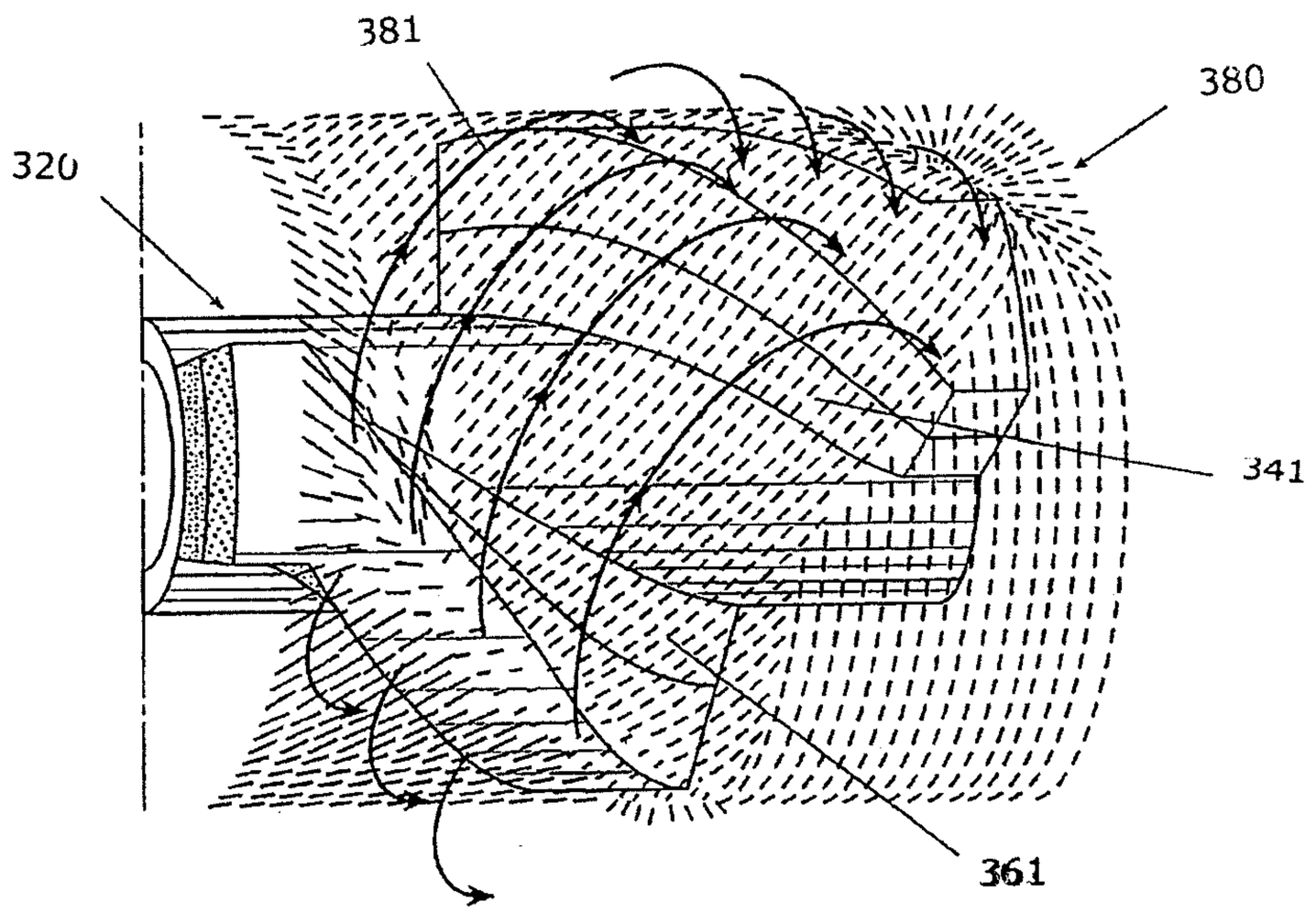


Fig. 8B

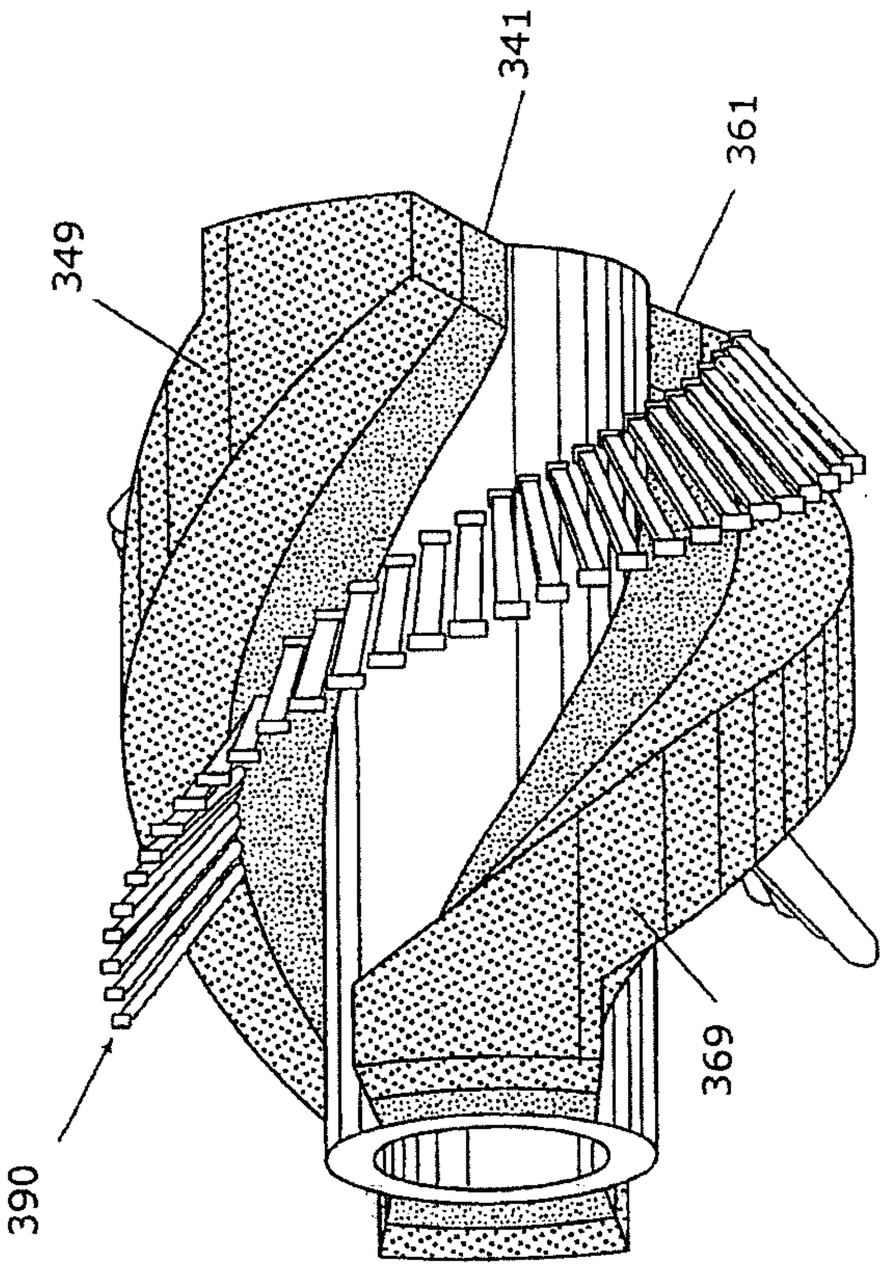


Fig. 9B

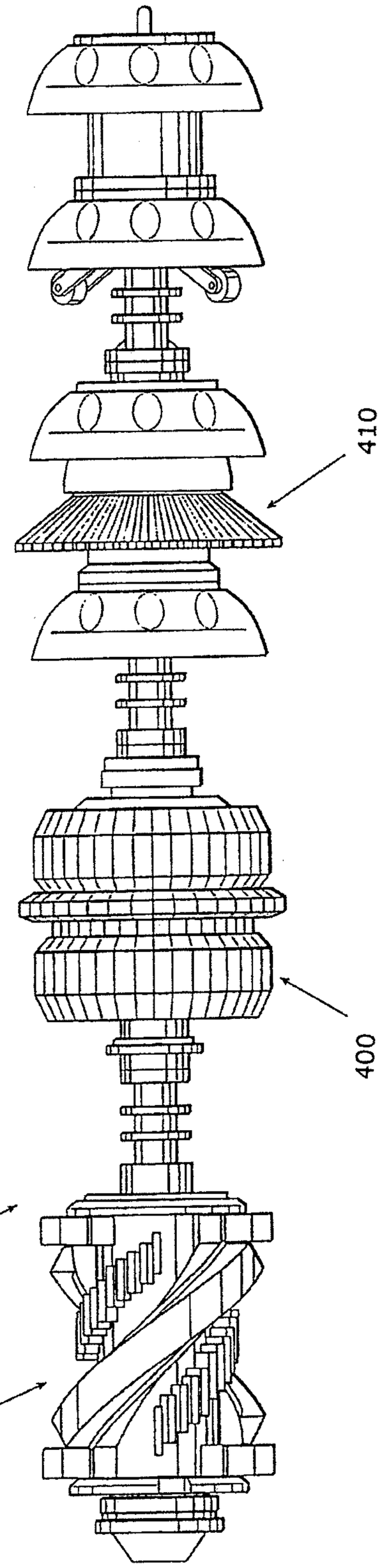


Fig. 11B

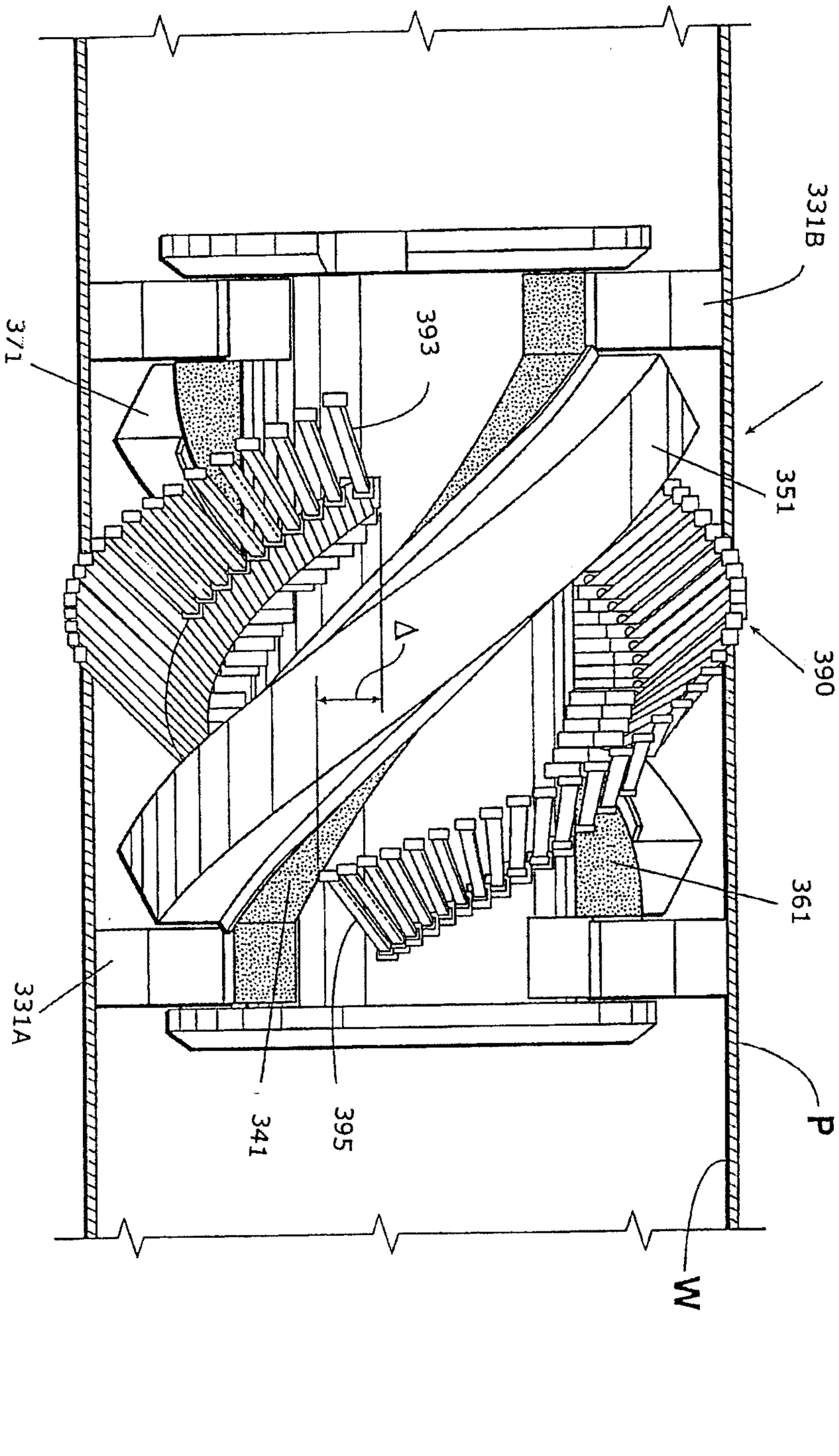
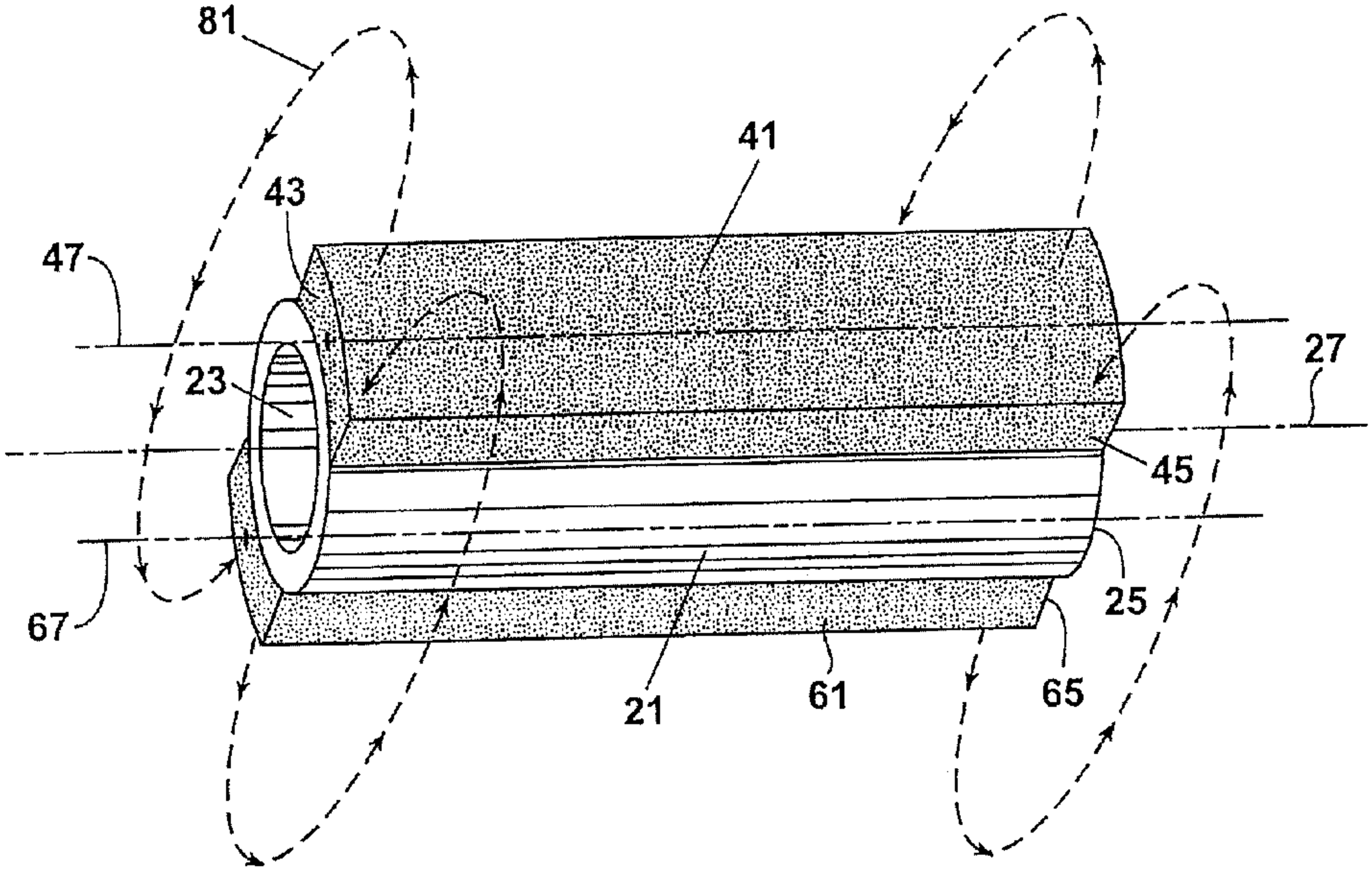


Fig. 10B


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