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(54) Title: METHOD FOR REDUCING THE VISCOUS FRICTION BETWEEN A FLUID AND AN OBJECT

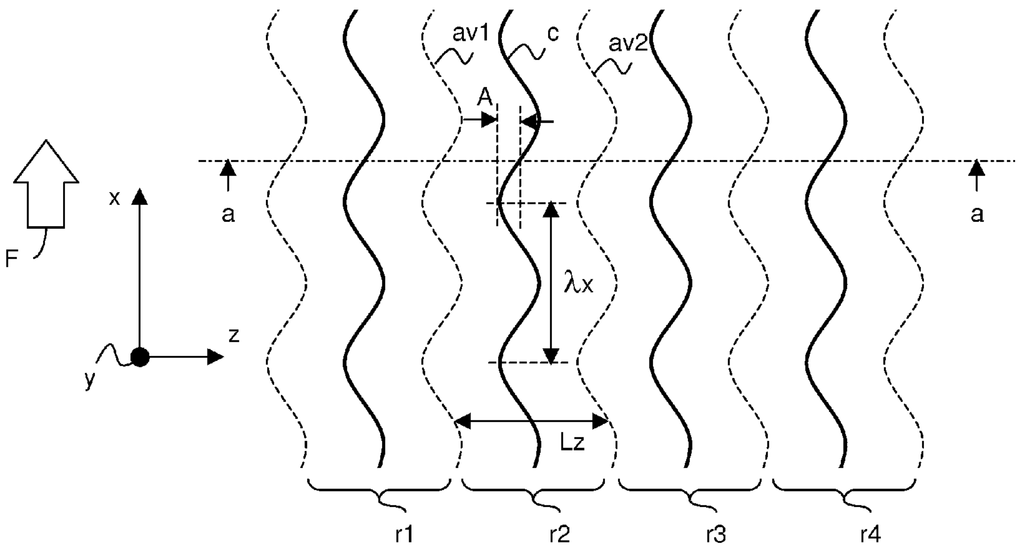

Figure 1a

(57) Abstract: It is disclosed a method for reducing the viscous friction due to the relative movement of a fluid and an object, wherein the object has an external surface in contact with a layer of the fluid and wherein the external surface has a base plane. The method comprises the following steps: forming on the external surface a plurality of projections projecting from the base plane; and imparting to the layer of fluid, by means of the plurality of projections, a profile with a periodic trajectory parallel to the base plane.

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"Method for reducing the viscous friction between a fluid and an object"

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DESCRIPTION

The present invention relates to a method for reducing the viscous friction due to the relative movement of a fluid and an object, in particular in the case of turbulent viscous friction. The present invention also relates to an object comprising an external surface configured so as to reduce the viscous friction due to the relative movement of a fluid and the object, in particular in the case of turbulent viscous friction.

As is known, when an object is in contact with a fluid and the object and the fluid move relative to each other, a frictional force (usually called "viscous friction") is produced as a result of the interaction between the surface of the object in contact with the fluid and the molecules of the fluid. This frictional force tends to reduce the velocity of the relative movement of object and fluid.

This situation arises in the case where an object moves in contact with a fluid which is substantially stationary (as, for example, with a moving aircraft, motor vehicle or ship) and in the case where the fluid moves with respect to the object which is substantially stationary (as, for example, with an oil pipe line, an aqueduct, etc., where the fluid flows inside pipes).

In the art it is known to reduce the viscous friction, in particular in the case of a turbulent flow, by forming a plurality of projections which are suitably shaped and suitably distributed over one or more zones of the surface of the object in contact with the fluid.

US 5,971,326 describes a surface for a wall which is subject to a turbulent flow having a main direction, where the surface has projecting ribs which have an elongated form in the main direction (called "riblets") and are spaced relative to each other in the direction perpendicular to the main direction of the flow. The projecting ribs have the function of reducing the turbulent exchange of moment between the flow and the wall along the surface. In this way it is possible to obtain a reduction in the friction of 7% compared to a smooth surface.

US 5,595,205 describes control of turbulence by means of a system with delta-shaped protrusions positioned in the transverse direction with respect to the direction of the flow.

US 6,345,791 describes a series of riblets extending longitudinally along a surface and having a triangular cross-section in the transverse direction. The apex of the cross-section defines a continuous, undulated ridge with peaks and valleys. Measured from the surface, the peaks have a greater height than the valleys. The interaction of the riblets with the structure of the turbulent boundary layer of the airstream reduces the skin friction drag coefficient of the surface by approximately 12% over an identical smooth surface without the riblets.

The present inventors have noted that the known solutions referred to above disadvantageously are not particularly efficient as regards reduction of the viscous friction.

In fact, with the known solutions referred to above, it is possible to achieve a reduction in the viscous friction equal to at the most 12% (in the case of US 6,345,791) in ideal conditions. However, in real conditions the geometry of the protuberances may be affected by the presence of impurities (for example dust) on the surface. This has the effect that the actual reduction of the viscous friction in real conditions is much less than the reduction calculated in ideal conditions. In some cases, the actual reduction in viscous friction in real conditions may be so low (for example, 1-2% in the case of an aircraft) that, considering the cost of manufacturing the surfaces with projections, the implementation of these solutions is not advantageous at all.

Therefore, the present inventors have faced the problem of providing a method for reducing the viscous friction due to the relative movement of a fluid and an object, in particular in the case of turbulent friction, which is able to overcome this drawback.

In particular, the present inventors have faced the problem of providing a method for reducing the viscous friction due to the relative movement of a fluid and an object, in particular in the case of turbulent friction, which is able to achieve a reduction in the viscous friction considerably greater than that of the known solutions, so that the actual reduction in friction in real conditions is high enough for use of the method to be advantageous.

According to a first aspect, the present invention provides a method for reducing the viscous friction due to the relative movement of a fluid and an object, wherein the object has an external surface in contact with a layer of the fluid, the external surface having a base plane. The method comprises the following steps: forming on the external surface a plurality of projections projecting from the base plane; and imparting to the layer of fluid, by means of the plurality of projections, a profile with a periodic trajectory parallel to the base plane.

Preferably, the periodic trajectory is a sinusoidal wave or a triangular wave or a square wave.

The periodic trajectory has a wavelength preferably of between 500 and 2000 viscous units, and more preferably of between 900 and 1250 viscous units.

Moreover, preferably, the periodic trajectory has an overall amplitude of between 100 and 500 viscous units.

According to the first embodiments, the step of forming comprises a step of forming on the external surface the plurality of projections which extend in a longitudinal direction of the flow, each of the plurality of projections having a peak which follows the periodic trajectory. According to these first embodiments, preferably, the step of forming comprises a step of forming on the external surface the plurality of projections parallel to each other and equally spaced in a transverse direction perpendicular to the longitudinal direction. Moreover, according to these first embodiments, preferably, the step of forming comprises a step of forming on the external surface the plurality of projections having a cross-section which is constant in the longitudinal direction.

According to second embodiments, the step of forming comprises a step of forming on the external surface the plurality of projections aligned in a transverse direction perpendicular to a longitudinal direction of the flow and arranged along the periodic trajectory in the longitudinal direction. According to these second embodiments, preferably, the step of forming comprises a step of forming on the external surface the plurality of projections, each of the plurality of projections having the form of a wedge with a triangular-shaped base, the triangle having a vertex directed in the direction opposite to that in which the flow travels. Moreover, according to these second embodiments, preferably, the step of providing comprises a step of forming on the external surface the plurality of projections, each of the plurality of projections having a height which is substantially equal to zero at the vertex.

According to a second aspect, the present invention provides an object comprising an external surface configured so as to reduce the viscous friction due to the relative movement of a fluid and the object, wherein the external surface has a base plane, the fluid having a layer in contact with the external surface. The object is characterized in that the external surface comprises a plurality of projections formed so as to impart to the layer of fluid a profile with a periodic trajectory parallel to the base plane.

The present invention will become clear from the description which follows, provided purely by way of a non-limiting example, to be read with reference to the accompanying drawings wherein:

- Figure 1a is a schematic top plan view of a portion of a surface of an object according to a first embodiment of the present invention;

- Figure 1b is a cross-sectional view along the plane a-a indicated in Figure 1a;

- Figure 2a is a schematic top plan view of a portion of a surface of object according to a second embodiment of the present invention;

- Figure 2b is a cross-sectional view along the plane b-b indicated in Figure 2a; and

- Figure 3 is a graph showing the percentage reduction in friction as a function of the oscillation wavelength.

Figures 1a, 1b, 2a and 2b show a set of three Cartesian axes the mutually perpendicular directions of which are indicated by x, y and z. In particular, the direction x coincides with the main direction of flow (indicated by the arrow F in Figures 1a and 2a) and will be referred to as "longitudinal direction". The direction y is the direction perpendicular to the plane of the surface and will therefore be referred to as "normal direction". Finally, the direction z perpendicular to the longitudinal direction x and parallel to the plane of the surface will be called "transverse direction".

The various figures are not shown in scale.

With reference to Figures 1a and 1b, a surface according to a first embodiment of the present invention will now be described in detail.

As shown in Figures 1a and 1b, according to this first embodiment, the surface has a base plane B parallel to the directions x and z. A plurality of projections project from the base plane B, extending in the longitudinal direction x preferably parallel to each other and preferably equally spaced in the transverse direction z . In Figures 1a and 1b, only four projections r1, r2, r3 and r4 are shown.

Herein after, the structure of the projection r2 alone will be described in detail. However, all the comments made with reference to the projection r2 are also applicable to all the other projections r1, r3 and r4 since they all have the same structure.

The projection r2 has preferably a cross-section which is constant in the longitudinal direction x. By way of example, in Figure 1b the projection r2 is shown as having a cross-section with a substantially triangular shape, the base of which coincides with the base plane B. However, this is only an example since the projection r2 could have the form of a blade (i.e. blade ribs or infinitely deep grooves) or of a parabola (scalloped grooves). The height of the projection r2, indicated as h in Figure 1b, is preferably between 5 and 35 viscous units, more preferably between 10 and 25 viscous units, and even more preferably is equal to 15 viscous units. As is known, a viscous unit is a length which depends on the kinematic viscosity of the fluid and the frictional velocity. For example, in the case of a aircraft flying at a height of 10000 m at a speed of 300 m/s, a viscous unit is equal to about 2.7 µm. Therefore, in this case, the height h of the projection r2 is preferably equal to $15 \cdot 2.7$ µm, namely about 40 µm.

The projection r2 has a peak c and is delimited by two valleys av1, av2 which are substantially parallel to the peak c. The distance between the valleys av1, av2, indicated in Figure 1a as Lz, corresponds both to the width of the projection r2, and to the distance between the projection r2 and the projections r1 and r3 adjacent to it. Preferably, the distance Lz is between 5 and 35 viscous units, more preferably between 10 and 25 viscous units, and even more preferably is equal to 15 viscous units. Therefore, in the example referred to above in which a viscous unit is equal to about 2.7 µm, the distance Lz is preferably equal to $15 \cdot 2.7$ µm, namely about 40 µm.

According to embodiments of the present invention, the peak c (and therefore also the valleys av1 an av2 parallel to them) follows, in the longitudinal direction x, a periodic trajectory which has an amplitude A and a wavelength λ_x. In particular, by way of example, the peak c shown in Figure 1a follows a sinusoidal trajectory which in mathematical terms is described by the following equation:

$$c(x) = A\sin\left(\frac{2\pi}{\lambda_x}x\right) \qquad [1]$$

This is only an example since the peak c could follow any periodic trajectory, for example square wave trajectory, triangular wave trajectory, etc. Preferably, the wavelength λ_x is between 500 and 2000 viscous units, more preferably between 900 and 1250 viscous units. Therefore, in the example above in which one viscous unit is equal to about 2.7 µm, the wavelength λ_x is preferably equal to 1250 · 2.7 µm, namely about 3.4 mm. Moreover, preferably, the amplitude A of the periodic trajectory is between 100 and 500 viscous units, more preferably is between 250 and 350 viscous units, and even more preferably is equal to 300 viscous units. Therefore, in the example above in which one viscous unit is equal to about 2.7 µm, the amplitude A is preferably equal to 300 · 2.7 µm, namely about 810 µm.

Advantageously, with the surface described above it is possible to achieve a reduction in friction considerably higher than the known solutions. In fact, owing to the fact that the peak of each projection has a transverse position variable in the longitudinal direction z, a discontinuity is introduced into the mechanism for interaction between the surface and the turbulence present in the layer of fluid in contact with the surface. More particularly, the turbulent structures present in the layer of fluid closest to the wall (namely those with a lower velocity), interacting with the wall, are displaced in the transverse direction in an alternating manner and therefore lose their phase relationship with the turbulent structures which are situated at a greater distance from the wall (namely the vortices). This mechanism advantageously weakens or even interrupts the viscous cycle of turbulence regeneration near the wall, since it creates a transversal alternate laminar boundary layer upon the wall. This advantageously reduces the viscous friction considerably, as will be described below with reference to Figure 3.

With reference to Figures 2a and 2b, a surface according to a second embodiment of the present invention will now be described in detail.

As shown in Figures 2a and 2b, also according to this second embodiment, the surface has a base plane B' which is parallel to the directions x and z and from which a plurality of projections project. In Figure 2a and 2b, for the sake of simplicity, only the projections d11, ... , d16, d21, ... , d26, d31, ... , d36, and d41, ... , d46 are shown.

Herein after, for the sake of simplicity, the structure of the projection d35 alone will be described. However, all the comments made in connection with the projection d35 are also applicable to all the other projections, since they have the same structure.

According to this second embodiment, the projection d35 has the form of a wedge with a substantially triangular shaped base. The vertex of the triangle is directed upstream, namely in the direction opposite to that in which the flow indicated by the arrow F travels. According to embodiments not shown in the drawings, the projection d35 may have the form described by US 5,595,205 (delta-shaped). The arrangement of the projections according to these embodiments is, however, different from that described by US 5,595,205, as will be described in greater detail herein below.

The projection d35 has a height which is substantially equal to zero at the vertex of the triangle and gradually increases up to a height h'. The height h' of the projection d35 is preferably between 1 and 10 viscous units, more preferably between 4 and 7 viscous units, and even more preferably, is equal to 5.5 viscous units. Therefore, in the example above in which a viscous unit is equal to about 2.7 µm, the height h' is preferably equal to $5.5 \cdot 2.7$ µm, namely about 15 µm.

The projection d35 has a width L'. The width L' is preferably between 100 and 300 viscous units, more preferably between 150 and 250 viscous units, and even more preferably is equal to 200 viscous units. Therefore, in the example above in which a viscous unit is equal to about 2.7 µm, the width L' is preferably equal to 200 · 2.7 µm, namely about 540 µm.

Preferably, the projections are arranged on the surface in a manner aligned in the transverse direction z. In particular, the projections d11, d21, d31 and d41 are aligned with each other in the transverse direction z and are equally spaced from each other by a distance indicated in Figures 2a as Lz', greater than the width L' of the single projection. The same comments are applicable to the projections d12, ... , d42, the projections d13, ... , d43, and including also the projections d16, ... , d46.

Preferably the distance Lz' is between 160 and 360 viscous units, more preferably between 210 and 310 viscous units, and even more preferably is equal to 260 viscous units. Therefore, in the example above in which a viscous unit is equal to about 2.7 µm, the distance Lz' is preferably equal to 260 · 2.7 µm, namely about 700 µm.

Moreover, preferably, the projections are arranged on the surface in the longitudinal direction z following a periodic trajectory. In particular, the projections d11, ... , d16 are arranged so that the respective vertices follow a periodic trajectory. The same comments are applicable to the projections d21, ... , d26, the projections d31, ... , d36 and the projections d41, ... , d46. The trajectories followed by the vertices of the projections d11, ... , d16, by the vertices of the projections d21, ... , d26, by the vertices of the projections d31, ... , d36 and by the vertices of the projections d41, ... , d46 preferably are parallel to each other.

Figure 2a, for the sake of simplicity, shows only the trajectory along which the projections d31, ... , d36 are arranged. The periodic trajectory has a wavelength λ_x'. In particular, by way of example, Figure 2a shows a sinusoidal trajectory which in mathematical terms is described by the following equation:

$$c'(x) = A'\sin\left(\frac{2\pi}{\lambda_x'}x\right) \qquad [2]$$

This is only an example since the projections could be arranged so as to follow any periodic trajectory, for example square wave trajectory, triangular wave trajectory, etc. In Figure 2a, the projections d31, ... , d36 are arranged so that four projections are included in a wavelength λ_x'. However, this is not limiting, since according to other embodiments a wavelength λ_x' may comprise a different number of projections. This number is preferably greater than or equal to 2.

Preferably the wavelength λ_x' is between 500 and 2000 viscous units, more preferably between 900 and 1250 viscous units. Therefore, in the example above in which a viscous unit is equal to about 2.7 µm, the wavelength λ_x' is preferably equal to 1250 · 2.7 µm, namely about 3.4 mm.

This second embodiment, therefore, is also advantageously able to achieve a reduction in friction considerably greater than that of the known solutions. In fact, in this second embodiment also the projections have a transverse position variable in the longitudinal direction z and therefore displace in the transverse direction the turbulent structures included in the layer of fluid closest to the wall, such that the latter lose their phase relationship with the turbulent structures situated at a greater distance from the wall. Therefore, advantageously, in this second embodiment also, the viscous wall cycle is weakened or even interrupted and therefore the viscous friction is reduced considerably.

Figure 3 is a graph showing the percentage reduction in friction DR(%), defined as:

$$DR(\%) = \frac{100 \cdot (D(smooth) - D(ribs))}{D(smooth)} \qquad [3]$$

where D(smooth) is the viscous friction of a smooth surface and D(ribs) is the viscous friction of the surface with projections. Figure 3 shows the progression of the percentage reduction in friction DR(%) upon variation of the oscillation wavelength λ_x. The oscillation wavelength λ_x is expressed in viscous units.

The graph shown in Figures 3 was obtained by means of direct numerical simulation of the Navier-Stokes equations in the uncompressible form. The numerical simulations were carried out by performing a spatial discretization using:

- Fourier modes in the longitudinal direction x (320 Fourier coefficients) and transverse direction z (192 Fourier coefficients); and
- 4th order compact finite difference schemes (160 points) in the normal direction y.

The rate of the flow F was kept constant during the simulation and therefore the reduction in viscous friction corresponds to the reduction in the longitudinal pressure gradient which must be applied to the flow in order to cause it flow with a constant flow rate. The dimensions of the wall used for the simulations are as follows: $21h_1$ in the longitudinal direction x and 6 h_1 in the transverse direction z, where h_1 is the half-height of the channel which was set to 200 viscous units. The dimension in the longitudinal direction z was in each case adjusted so as to contain an integer number of wavelengths λ_x. Each simulation was performed for a time period $1000U_p/h_1$, where U_p is the central velocity of a laminar flow with the same flow rate. The simulations were performed on a supercomputer comprising 10 Xeon PCs with a dual processor connected together in a ring.

During the simulations, the amplitude A of the periodic trajectory was set to 350 viscous units and it was simulated using Taylor's frozen turbulence hypothesis and the convective character of the flow in the vicinity of the wall.

From the graph shown in Figure 3 it can be seen that, for wavelengths λ_x of between about 500 and 2000 viscous units, the reduction in friction DR(%) is greater than 40% and, for a wavelength λ_x between about 900 and 1250 viscous units, there is a maximum value where DR(%) is equal to about 45%.

Therefore, advantageously, with the surface according to embodiments of the present invention it is possible to achieve a reduction in the viscous friction considerably greater than that possible with the known solutions (reduction of more than 50% compared to the reduction of 12% obtained by US 6,345,791). This increase in the reduction of friction is so high that the use of the surface is advantageous even when taking into account the cost of manufacture of the surface itself.

CLAIMS

1. A method for reducing the viscous friction due to the relative movement of a fluid and an object, said object having an external surface in contact with a layer of said fluid, said external surface having a base plane (B, B'), wherein the method comprises the following steps:
   - forming on said external surface a plurality of projections (r1, ... , r4; d11, ... , d16; d41, ... , d46) projecting from said base plane (B, B'); and
   - imparting to said layer of said fluid, by means of said plurality of projections (r1, ... , r4; d11, ... , d16; d41, ... , d46), a profile with a periodic trajectory parallel to said base plane (B, B').
2. The method according to claim 1, wherein said periodic trajectory is a sinusoidal wave.
3. The method according to claim 1, wherein said periodic trajectory is a triangular wave.
4. The method according to claim 1, wherein said periodic trajectory is a square wave.
5. The method according to any one of the preceding claims, wherein said periodic trajectory has a wavelength (λx) of between 500 and 2000 viscous units.
6. The method according to claim 5, wherein said periodic trajectory has a wavelength (λx) of between 900 and1250 viscous units.
7. The method according to any one of the preceding claims, wherein said periodic trajectory has an amplitude (A) of between 100 and 500 viscous units.
8. The method according to any one of the preceding claims, wherein the step of forming comprises a step of forming on said external surface said plurality of projections (r1, ... , r4) which extend in a longitudinal direction (x) of said flow, each of said plurality of

projections (r1, ... , r4) having a peak (c) which follows said periodic trajectory.

9. The method according to claim 8, wherein the step of forming comprises a step of forming on said external surface said plurality of projections (r1, ... , r4) parallel to each other and equally spaced in a transverse direction (z) perpendicular to said longitudinal direction (x).

10 The method according to claim 8 or 9, wherein the step of forming comprises a step of forming on said external surface said plurality of projections (r1, ... , r4) having a constant cross-section in said longitudinal direction (x).

11. The method according to any one of claims 1 to 7, wherein the step of forming comprises a step of forming on said external surface said plurality of projections (d11, ... , d16; d41, ... , d46) aligned in a transverse direction (z) perpendicular to a longitudinal direction (x) of said flow and arranged along said periodic trajectory in said longitudinal direction (x).

12. The method according to claim 11, wherein the step of forming comprises a step of forming on said external surface said plurality of projections (d11, ... , d16; d41, ... , d46), each of said plurality of projections (d11, ... , d16; d41, ... , d46) having the form of a wedge with a triangular shaped base, said triangle having a vertex directed in the opposite direction to that in which said flow travels.

13. The method according to claim 12, wherein the step of forming comprises a step of forming on said external surface said plurality of projections (d11, ... , d16; d41, ... , d46), each of said plurality of projections (d11, ... , d16; d41, ... , d46) having a height which is substantially zero at said vertex.

14. An object comprising an external surface configured to reduce the viscous friction due to the relative movement of a fluid and the

object, said external surface having a base plane (B, B'), said fluid having a layer in contact with said external surface, characterized in that the external surface comprises a plurality of projections (r1, ... , r4; d11, ... , d16; d41, ... , d46) shaped so as to impart to said layer of said fluid a profile with a periodic trajectory parallel to said base plane (B, B').

15. The object according to claim 14, wherein each of said plurality of projections (r1, ... , r4) extends in a longitudinal direction (x) of said flow and has a peak (c) which follows said periodic trajectory.
16. The object according to claim 15, wherein said plurality of projections (r1, ... , r4) are parallel to each other and equally spaced in a transverse direction (z) perpendicular to said longitudinal direction (x).
17. The object according to claim 15 or 16, wherein each of said plurality of projections (r1, ... , r4) has a constant cross-section in said longitudinal direction (x).
18. The object according to claim 14, wherein said plurality of projections (d11, ... , d16; d41, ... , d46) are aligned in a transverse direction (z) perpendicular to a longitudinal direction (x) of said flow and arranged along said periodic trajectory in said longitudinal direction (x).
19. The object according to claim 18, wherein each of said plurality of projections (d11, ... , d16; d41, ... , d46) has the form of a wedge with a triangular shaped base, said triangle having a vertex directed in the opposite direction to the direction in which said flow travels.
20. The object according to claim 19, wherein each of said plurality of projections (d11, ... , d16; d41, ... , d46) has a height which is substantially zero at said vertex.
21. The object according to any one of claims 14 to 20, wherein said periodic trajectory is a sinusoidal wave.

22. The object according to any one of claims 14 to 20, wherein said periodic trajectory is a triangular wave.
23. The object according to any one of claims 14 to 20, wherein said periodic trajectory is a square wave.
24. The object according to any one of claims 14 to 20, wherein said periodic trajectory has a wavelength (λx) of between 500 and 2000 viscous units.
25. The object according to claim 24, wherein said periodic trajectory has a wavelength (λx) between 900 and 1250 viscous units.
26. The object according to any one of claims 14 to 25, wherein said periodic trajectory has an amplitude (A) of between 100 and 500 viscous units.

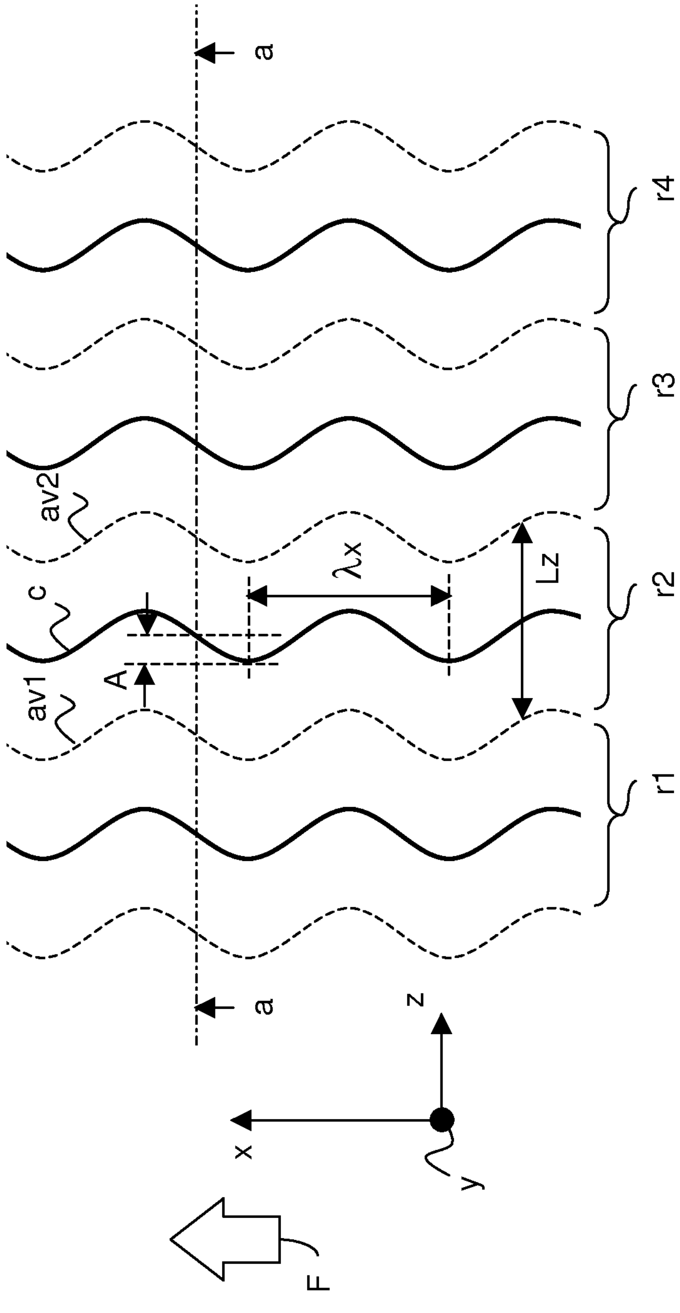

Figure 1a

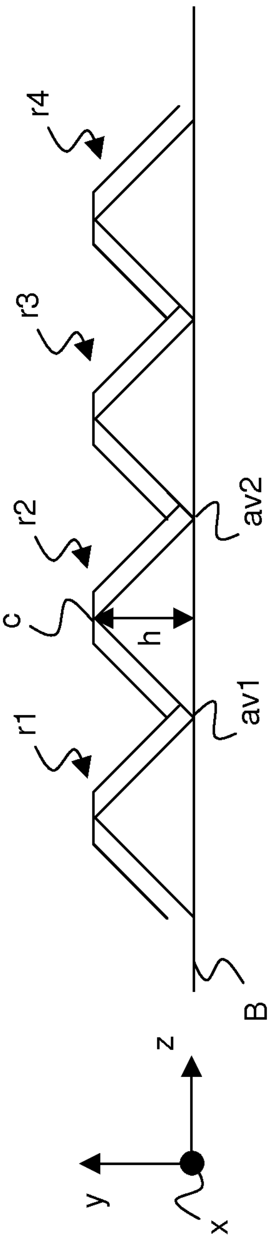

Figure 1b

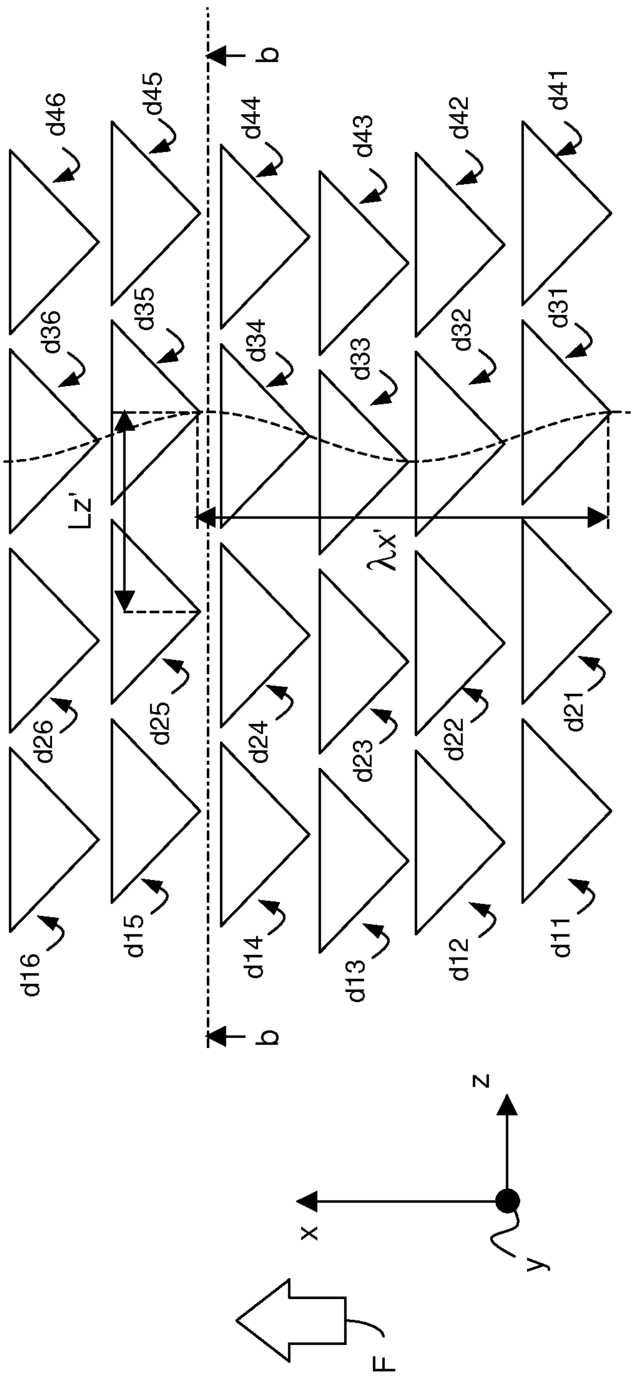

Figure 2a

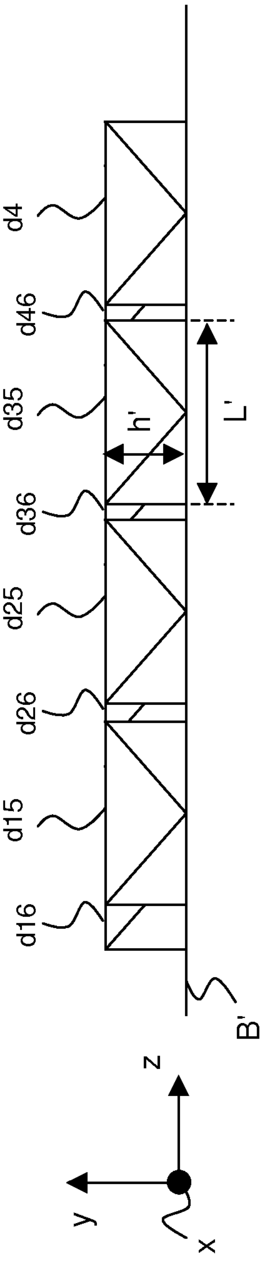

Figure 2b

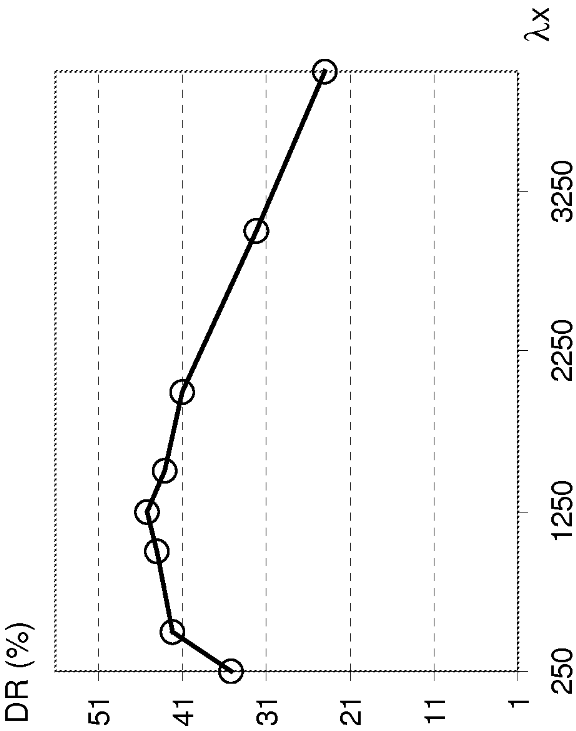

Figure 3

NTERNATIONAL SEARCH REPORT

International application No
PCT/EP2008/057622

A. CLASSIFICATION OF SUBJECT MATTER
INV. F15D1/06 F15D1/12

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)
F15D

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 practical, 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.
X	US 2004/155150 A1 (KROHMER CHRISTOPH [DE] ET AL) 12 August 2004 (2004-08-12) paragraphs [0040] - [0043], [0053] - [0056]; claims 1,4; figures 1a,1b,1c	1,2,8, 10,11, 14,15, 17,18,21
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☒ Further documents are listed in the continuation of Box C.

☒ See patent family annex.

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

INTERNATIONAL SEARCH REPORT

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