

Nov. 25, 1947.

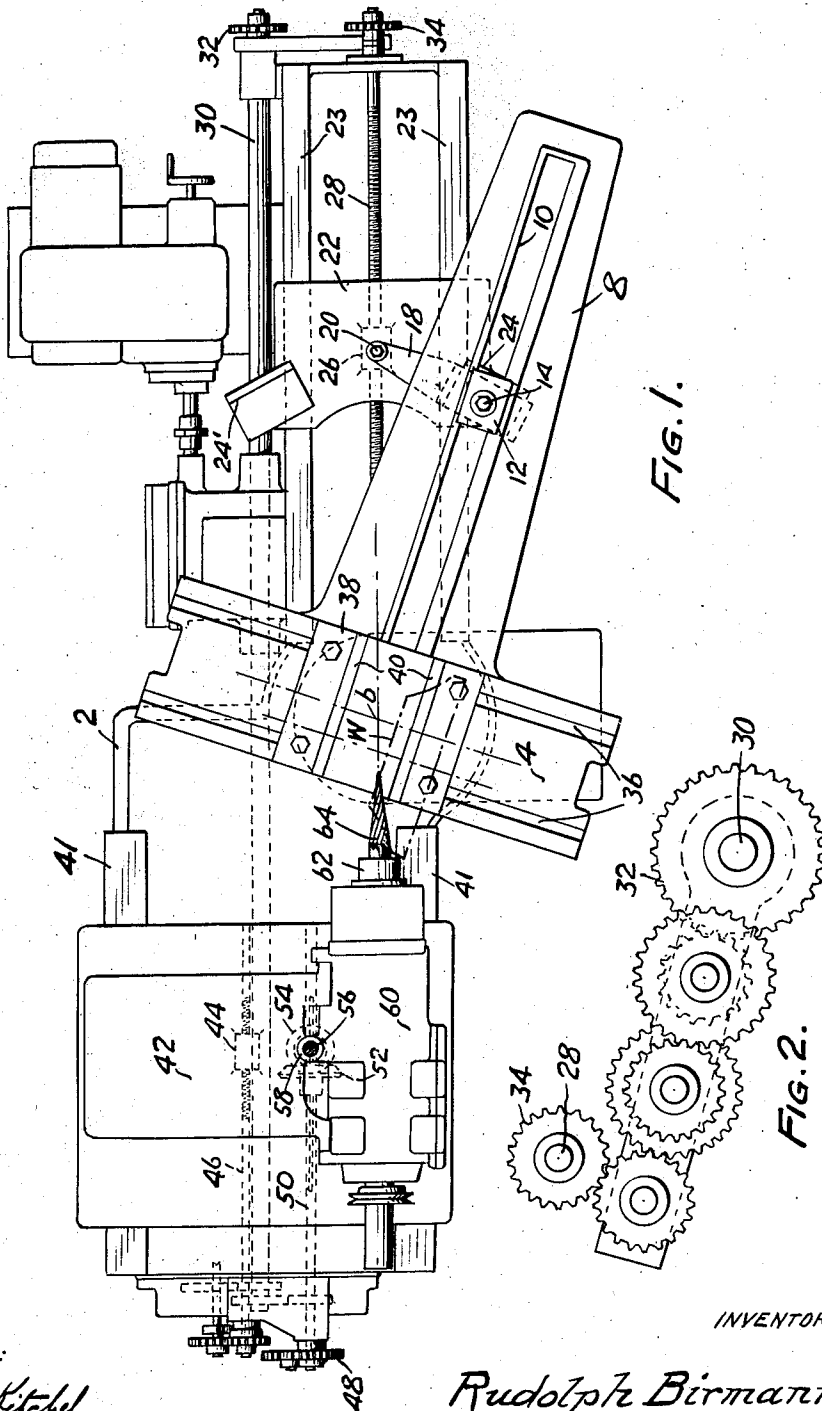
R. BIRMANN

2,431,604

METHOD AND MACHINE FOR GENERATING ROTORS FOR ELASTIC FLUID MECHANISM

Filed March 26, 1943

6 Sheets-Sheet 1



WITNESS:

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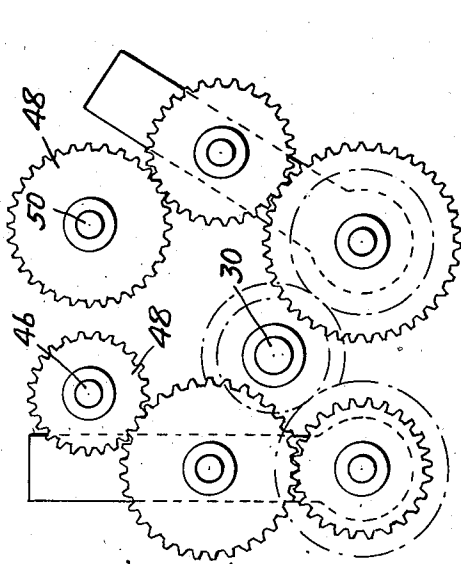
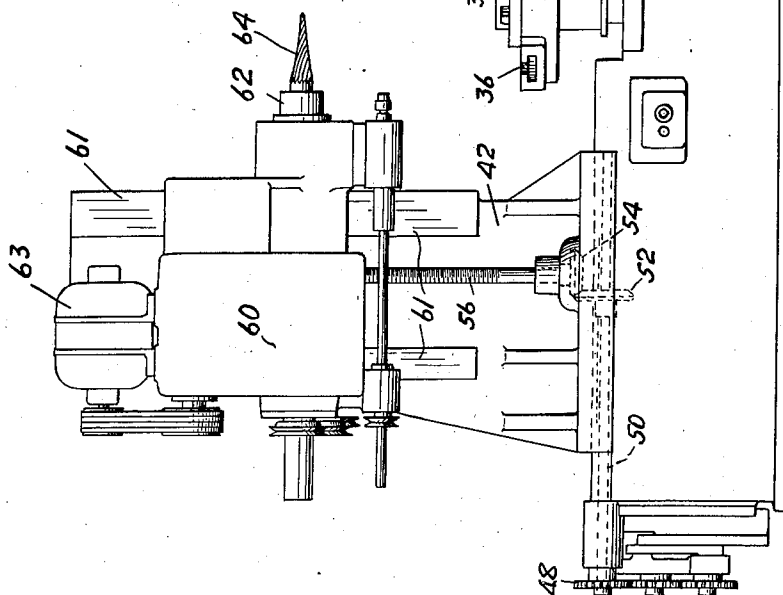
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METHOD AND MACHINE FOR GENERATING ROTORS FOR ELASTIC FLUID MECHANISM

Filed March 26, 1943

6 Sheets-Sheet 2



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METHOD AND MACHINE FOR GENERATING ROTORS FOR ELASTIC FLUID MECHANISM

Filed March 26, 1943

6 Sheets-Sheet 3

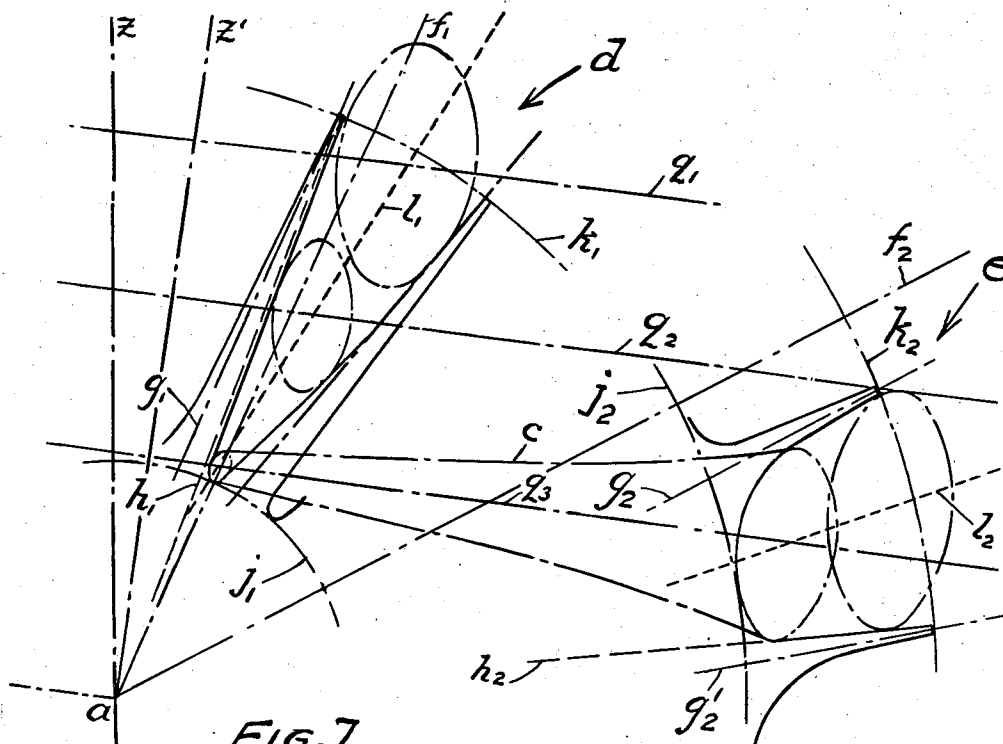


FIG. 7.

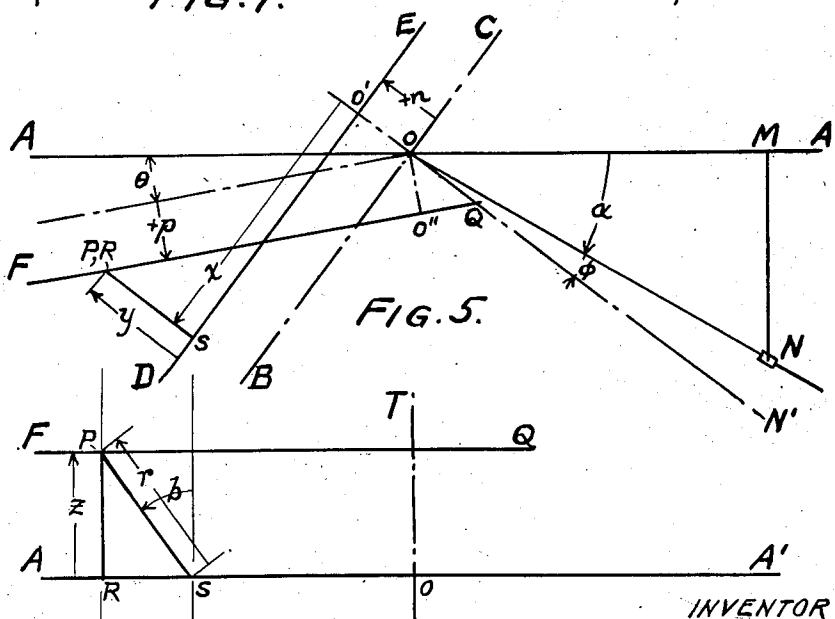


FIG. 5.

FIG. 6.

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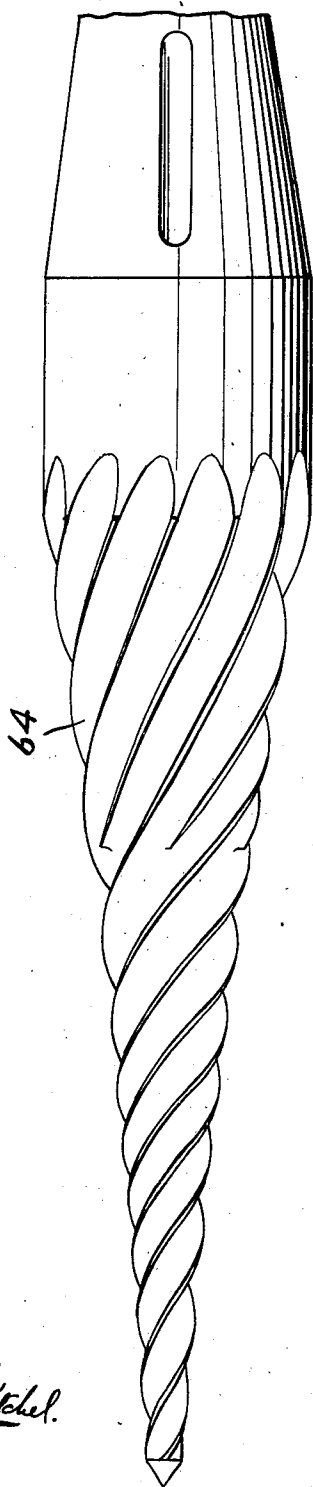
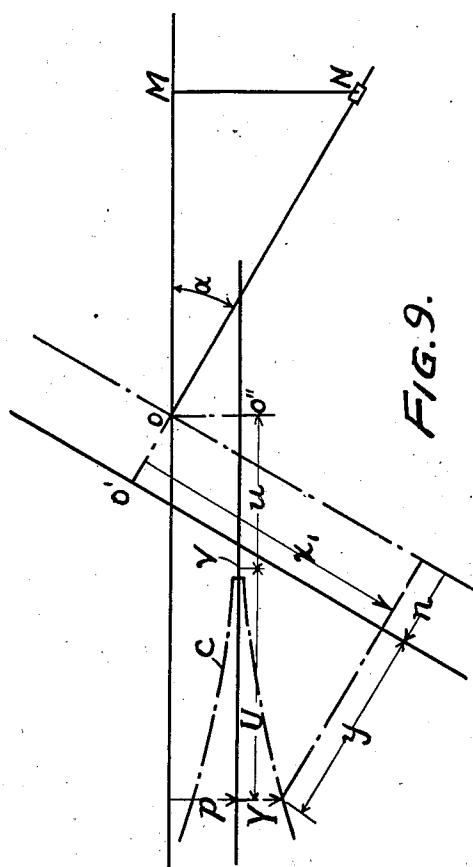
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2,431,604

METHOD AND MACHINE FOR GENERATING ROTORS FOR ELASTIC FLUID MECHANISM

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6 Sheets-Sheet 4



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METHOD AND MACHINE FOR GENERATING ROTORS FOR ELASTIC FLUID MECHANISM

Filed March 26, 1943

6 Sheets-Sheet 5

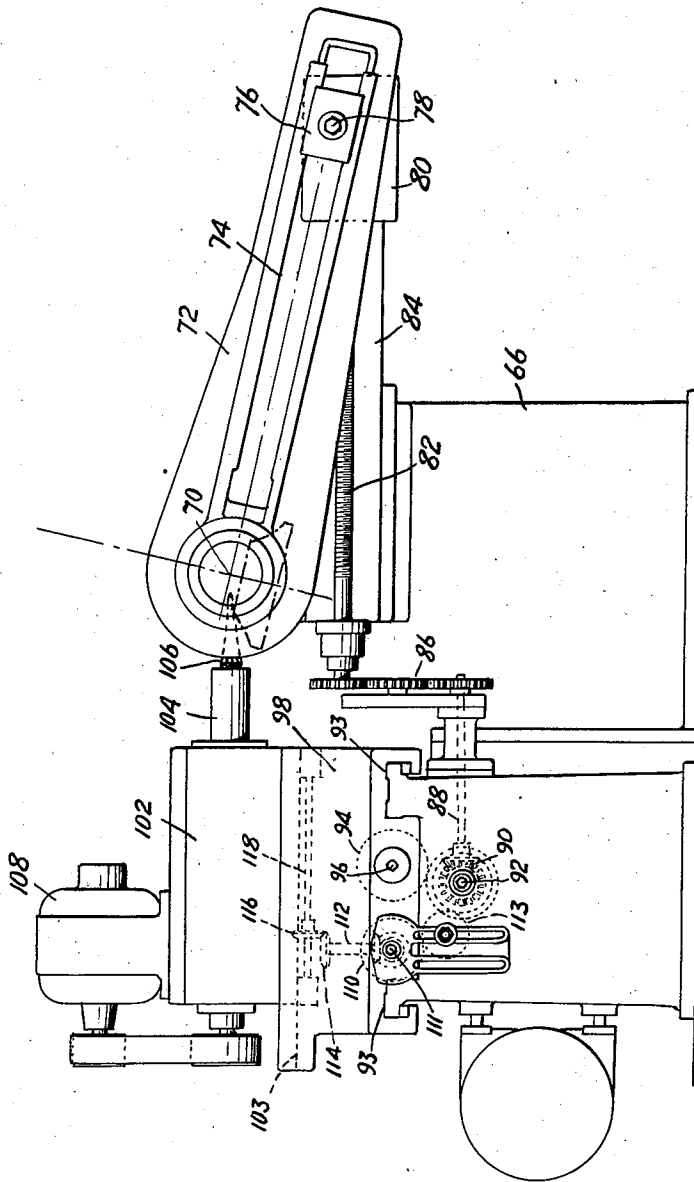


FIG. 10.

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METHOD AND MACHINE FOR GENERATING ROTORS FOR ELASTIC FLUID MECHANISM

Filed March 26, 1943

6 Sheets-Sheet 6

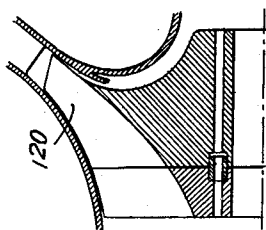


FIG. 13.

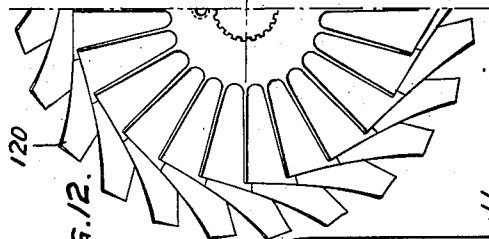


FIG. 12.

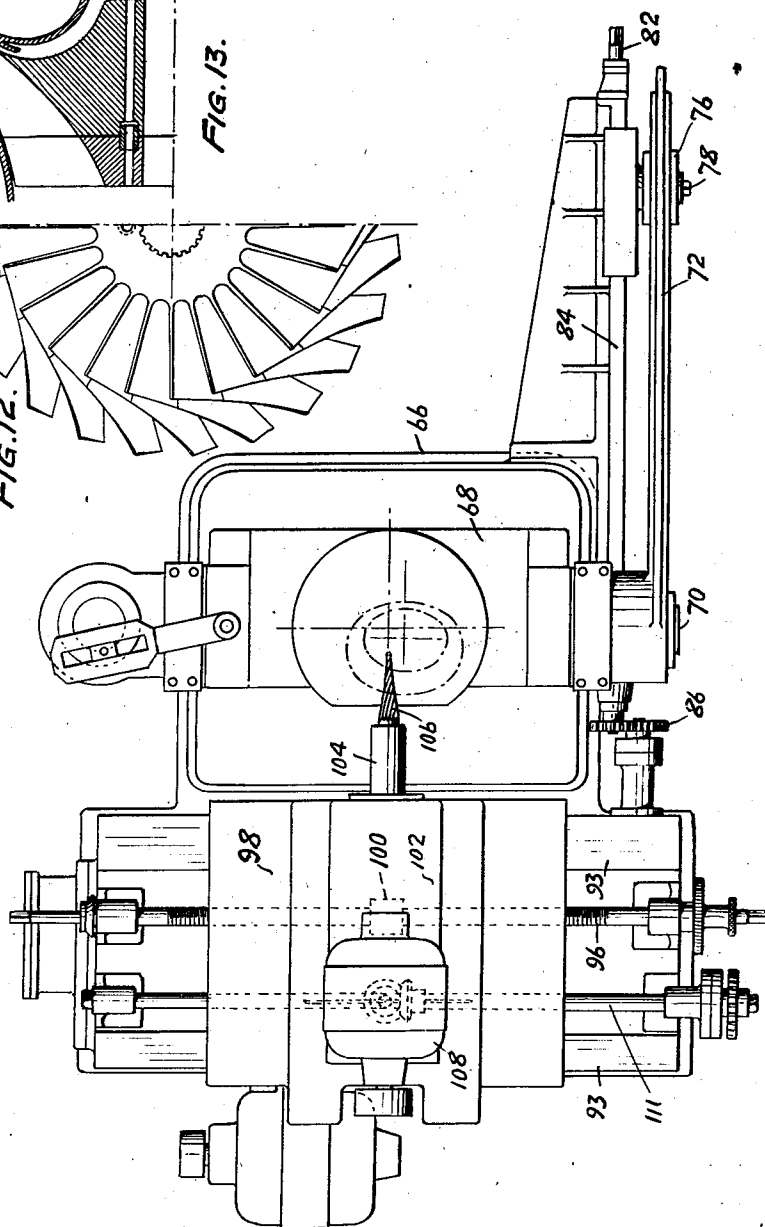


FIG. 11.

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UNITED STATES PATENT OFFICE

2,431,604

METHOD AND MACHINE FOR GENERATING
ROTORS FOR ELASTIC FLUID MECHANISM

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mesne assignments, to Turbo Engineering Cor-
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Application March 26, 1943, Serial No. 480,633

14 Claims. (Cl. 90—13.9)

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This invention relates to a method and machine for generating rotors, for example, centrifugal impellers and turbine rotors, for elastic fluid mechanism and to the improved rotors generated thereby. Specifically, the invention relates to the provision of the type of rotors for elastic fluid mechanism which are disclosed in my Patents 1,926,225, dated September 12, 1933, 1,959,703, dated May 22, 1934, and 2,283,176, dated May 19, 1942, and my application Serial No. 441,686, filed May 4, 1942.

As disclosed in said patents and application, there are highly desirable, for the handling of elastic fluid, rotors having passages defined by vanes conforming to the disclosures thereof. In particular, such rotors are desirably formed by having the passages thereof milled out of solid blanks of metal so as to achieve maximum strength at very high speeds of operation, and in the case of turbine rotors, ample conduction of heat from the vanes to the central portions of the rotor to avoid overheating of the vanes which might result in their destruction. As pointed out in the disclosures aforementioned, the vanes and passages, when made to conform closely to particular theoretical surfaces, have highly desirable aerodynamic, as well as mechanical, properties. They are adapted to receive the elastic fluid and discharge it in the proper directions, and there are securable the proper curvature and divergence of the elastic fluid passages to give rise to smooth flow despite extremely high speeds of operation.

One broad object of the present invention is the provision of a novel method for the generation of elastic fluid rotors of the type indicated. A further broad object of the invention is the provision of a machine for carrying out automatically the aforesaid method and capable of adjustment to secure desirable variations in the surfaces generated. Various detailed objects of the invention which will become apparent hereafter have to do with details of both the methods and the machines whereby, in particular, the generation may be carried out in such fashion that both sides of a fluid passage may be simultaneously cut.

A further object of the invention is the provision of a centrifugal impeller wherein, without violation of other requirements, there is secured

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a quite large angle about the axis of rotation between the inlet and outlet portions of each of its passages. A subsidiary object is the cutting of such an impeller in one operation, whereas heretofore it has been generally necessary to take successive cuts to secure the desired result.

These and other detailed objects of the invention will become apparent from the following description, read in conjunction with the accompanying drawing, in which:

Figure 1 is a plan view of one form of machine provided in accordance with the invention for the generation of such rotors;

Figure 2 is an elevation showing certain gear change mechanism of the machine, in particular looking at the right hand end of the machine as viewed in Figure 1;

Figure 3 is an elevation of the machine of Figure 1, partially in section, to illustrate certain details;

Figure 4 is an elevation of certain gear change mechanism as viewed looking at the left hand end of Figure 3;

Figure 5 is a diagram showing in plan the principal elements of the machine of Figure 1 and serving to make clear the nature of the surfaces generated thereby;

Figure 6 is a similar diagram of the same matter in elevation;

Figure 7 is a diagrammatic elevation indicating two radial sections through an impeller formed in accordance with the invention illustrating in particular how the impeller passages are generated and the fashion in which the angle between the inlet and outlet is increased;

Figure 8 is an elevation of the type of cutter used for the generation of the passages;

Figure 9 is a view, generally similar to Figure 5, but provided in particular to illustrate the fashion in which a cutter generates both sides of an impeller passage simultaneously;

Figure 10 is a side elevation of an alternative form of machine provided in accordance with the invention;

Figure 11 is a plan view of the machine of Figure 10; and

Figures 12 and 13 show in diagrammatic elevation and axial section, respectively, an impeller of the type generated.

There will first be described the physical as-

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pects of the machine of Figures 1 to 4, the nature of the operations performed thereby being thereafter described.

The machine of these figures is essentially a milling machine in which both the cutter and the work are movable in predetermined definite relationship to secure the generation of skew surfaces. The machine comprises a bed 2 on which there is mounted a work carrier 4 for rotation about a vertical axis 6, the position of which may, if desired, be made adjustable transversely of the machine. The work carrier 4 is provided with an arm 8 slotted as indicated at 10 to provide a trackway for the reception of a cross-head 12, which is pivoted, as indicated at 14, to a block adjustable along a guide way 16 extending radially of an arm 18, which is secured at 20 to a carriage 22 movable on tracks 23. The pivot 14 is arranged to be fixed in adjusted position radially of the arm 18, while the arm 18 is adapted to be swung between two positions defined by stop elements 24 and 24' at opposite sides of, and secured to, the carriage 22. The provision for swinging the arm 18 to either of these two positions is merely to make it easily possible to generate right hand and left hand rotors. As will become evident hereafter in discussing the theory of operation, the fact that the arm 18 extends at an acute angle with respect to the axis of the machine is not significant and, in fact, this arrangement is provided solely to make possible certain clearances when the carriage 22 reaches an extreme left hand position. The adjustment of the pin 14 is solely for the purpose of adjusting it transversely of the longitudinal axis of the machine, this adjustment alone being of interest.

The carriage 22 is provided with a nut 26 which embraces the carriage-driving screw 28, driven from the main shaft 30 of the machine through change speed gearing comprising the end elements 32 and 34 and indicated in Figure 2. The work support 4 is provided with grooves as indicated at 36, along which there may be adjusted the table 38, which in turn carries tracks 40 so that the work W may be adjusted in the direction of the tracks, i. e., in the direction of the length of the trackway 10. It will be evident from the above that the work may be adjusted both in the direction of the trackway 10 and transversely of that direction relative to the vertical axis 6 about which rotation may take place by reason of the travel of the cross-head 12 along the trackway 10. In addition, if desired, the vertical axis 6 may be adjusted transversely of the direction of the screw 28.

A carriage 42 supports the cutter and is arranged to slide in the direction of the axis of the screw 28 along the tracks 41 provided on the machine bed. A nut 44 carried by the carriage 42 embraces a screw 46, connected to a gear 48 (Figure 4) driven through change speed gearing from the main shaft 30. A shaft 50, whose gear 48 is driven through change speed gearing from the main shaft 30, as indicated in Figure 4, has splined thereto a bevel pinion 52 meshing with a second bevel pinion 54 carried by a vertical screw 56 mounted in the carriage, the bevel pinion 52 being so mounted as to move with the carriage lengthwise of the shaft 50. The vertical screw 56 is embraced by a nut 58 carried by the support 60 movable vertically relative to the carriage 42 along the trackways 61 of the latter. The support 60 has mounted in bearings therein the spindle 62 in which may be fitted the various

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milling cutters 64, the support also carrying the driving motor 63 for this spindle.

As a result of the construction indicated, it will be evident that the cutter is movable both in the direction of its axis of rotation, which is parallel to the tracks 41, and also vertically by reason of the mounting of its support on the tracks 61.

In Figures 5 and 6 there are illustrated diagrammatically the fundamental elements of the machine of Figures 1 to 4. In these Figures 5 and 6, the axis of rotation of the work is indicated at OT through which there extends the horizontal line AOA' parallel to the axis of the screw 28 and to the tracks 23. Along this line AOA' there moves the foot M of a horizontal perpendicular MN, the length of which, though subject to adjustment, is fixed during any particular operation of the machine, the point N corresponding to the pivot of the crosshead 12 arranged to slide along the line ON which may be considered fixed to the work support pivoted about OT. For the purpose of greater generality of analysis, there are involved in Figures 5 and 6 adjustments in addition to those described in connection with the physical machine. For example, DE represents the axis (horizontal) of the blank being cut which axis, however, is not perpendicular to ON but to a line ON' making with ON the angle ϕ . BC is perpendicular to ON' and parallel to DE at a distance n representing the displacement of the axis of the work from the axis OT of rotation.

FQ is the axis of the cutter, extending horizontally at a distance z from the common horizontal plane of AA', ON, DE and BC, and for generality assumed making an angle θ with the direction AA' and displaced horizontally by a distance p from the axis OT.

It will be evident that Figures 5 and 6 represent the essentials of the machine with some further generality introduced by the angles θ and ϕ and the displacement p . While the physical form of the machine involves some vertical and horizontal displacements of the physical equivalents of the diagrammed lines it will be evident that what is accomplished by the machine is identically what would be accomplished by the diagrammed mechanism.

First there will be considered the theoretical surface which would be generated by a cutter of zero diameter, i. e., by the cutter axis FQ. This involves seeking an equation for an arbitrary point P on FQ in terms of coordinates tied to the work. Let PR be the perpendicular from the arbitrary point P to the plane AON, and RS the perpendicular to line DE from R. As origin consider point O' the foot of the perpendicular from O to DE, the rotor axis, and let x be measured along the axis DE in the direction O'S, y perpendicular to DE in a horizontal plane in the direction SR, and z vertically in the direction RP. For the purpose of the present analysis, these rectangular coordinates will be most convenient. For comparison with the aforementioned patents and application, related cylindrical coordinates x , b and r may be noted, related to x , y , and z as follows:

$$\begin{aligned} x &= x \\ y &= r \sin b & r &= \sqrt{y^2 + z^2} \\ z &= r \cos b & \tan b &= \frac{y}{z} \end{aligned}$$

by which relationships transformation from one

set of coordinates to the other may be readily effected.

As will be evident from the machine, the point M moves along AA' towards the right as the cutter axis FQ moves vertically in the direction of increasing z at a definite ratio of speeds determined by the change gearing. From this and the geometry of Figures 5 and 6, the equations of the surface generated are:

$$1. \quad y = \frac{x}{\tan(\alpha + \theta + \phi)} - \frac{p}{\sin(\alpha + \theta + \phi)} - n$$

$$z = K_1 \left(\frac{1}{\tan \alpha} \right) - K_2$$

These are parametric equations for the surface in terms of the parameter α , the angle MON, which cannot be eliminated from these general equations without giving rise to a very complicated single equation.

K_1 in the above is the product of the length of MN by the ratio of the rate of movement of z to that of point M.

If, theoretically, M reached O, z would then have the value $-K_1 K_2$; in other words, K_2 is related to the initial relative settings of the cutter axis and point M.

It will be noted from the above equations that the angles θ and ϕ are additive, i. e., the same effect of adjustment of both could be secured by adjustment of one, or if they were of different signs they would tend to neutralize each other. There is, therefore, no point in setting the cutter axis FQ off parallelism with the axis AA', the same effect being securable by turning the blank on the table to change ϕ . As a matter of fact, adjustment of ϕ is not generally desirable (causing the vanes generated to depart from radial condition) and hence in the following θ and ϕ will both be considered zero. Only under special conditions may θ and ϕ be introduced to advantage, for example, to correct curvatures otherwise introduced.

If $\theta + \phi = 0$, the equations reduce to:

$$2. \quad y = \frac{x}{\tan \alpha} - \frac{p}{\sin \alpha} - n$$

$$z = K_1 \left(\frac{1}{\tan \alpha} \right) - K_2$$

The adjustment of p different from zero is also a disturbing factor unless it is properly related to the other constants. As will be evident from the form of these equations, radial sections of the surface ($x = \text{constant}$) are not straight lines, curvature being introduced by the constant p . Slight values of the constant p may be used, however, without detrimental deviation from straight line values of these sections. It is also possible to use quite large values of p provided the other constants are properly chosen, particularly to obtain for impellers quite large angles between the entrance and exit portions of the fluid passages.

If p is zero, there are obtained the surfaces to which, and to the generation of which, the present application is primarily directed. The equations then become:

$$3. \quad y = \frac{x}{\tan \alpha} - n$$

$$z = K_1 \left(\frac{1}{\tan \alpha} \right) - K_2$$

From these the parameter may be readily eliminated giving the single equation for the surface:

4.

$$\frac{z}{K_1} + K_2 = \frac{y + n}{x}$$

As will be obvious from the last equation, any radial section, x constant, will be a straight line. The straight line, however, will not be radial unless $n - K_2 x = 0$. Since x varies from inlet to outlet, it is possible to choose n and K_2 so that at the inlet $n - K_2 x$ is positive whereas at the outlet, x being then greater, $n - K_2 x$ is negative with both of these limiting deviations from zero small. In this fashion, advantageous results may be secured as pointed out below.

If $n = 0$ and $K_2 = 0$, the equation becomes:

5.

$$x = K_1 \frac{y}{z}$$

or, changing to cylindrical coordinates,

$$x = K_1 \tan b$$

the equation of the surface disclosed and discussed in the aforementioned patents and application. As will be pointed out hereafter, the surfaces generated in accordance with the present invention may conform very closely either to a single surface given by $x = K \tan b$, or a plurality of such surfaces fitted together, the advantage arising in the latter case being that a single generation serves to provide a complete surface which would otherwise require separate successive generating operations.

The application of the above to the generation of an impeller or turbine wheel will be next described with reference to Figure 7, in which generation will be assumed in accordance with Equation 3 or 4. In this figure, a indicates the axis of the wheel being generated ($= DE$ of Figure 5) and az is the trace of the xz plane, the angle b being measured positive in a clockwise direction and y being measured horizontally to the right. The entrance portion of an impeller passage is illustrated at d and the exit portion of the same passage at e . The former will be regarded as located at $x = x_1$, and the latter at $x = x_2$, various illustrated elements being located in said planes. It is assumed that the constants K_1 , K_2 and n have been set by adjustment of the machine. Preliminarily we will again consider generation of surfaces by the axis of the cutter, passing later to the effect of using a real cutter of particular type.

At f_1 and f_2 there are indicated the radial lines corresponding to the intersection of the planes $x = x_1$ and $x = x_2$ with the surface $x = K_1 \tan b$, i. e., the surface which would be generated by making K_2 and n zero in Equation 3 or 4.

Assume further that n and K_2 are so chosen as above so that $n - K_2 x_1$ is positive and $n - K_2 x_2$ is negative. The element g_1 of the general generated surface then, in accordance with what was proved above, lies to the left of f_1 , parallel to f_1 and at a distance therefrom determined by the choice of constants and the value of x_1 .

The element g_2 of the same surface lies to the right of f_2 , parallel to f_2 and at a distance determined by the choice of constants and the value of x_2 .

Obviously for some intermediate value of x for which $n - K_2 x = 0$, the element of the generated surface will be truly radial and coincident with the element f of $x = K_1 \tan b$ and the maximum deviations from radial condition will occur at g_1 and g_2 . It will thus be seen that, for the indicated relation of n and K_2 , the generated surface will pass from one side of $x = K_1 \tan b$ to the other in the direction of increasing b with

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the result that between x_1 and x_2 it will subtend a greater angle than the latter; in the diagram, for example, the latter subtends about 37° , whereas the former subtends about 47° .

As pointed out in my said application Serial Number 441,686, this is very advantageous in reducing the loading on the blading. Surfaces built upon the theoretical surface thus generated have, however, a limitation in that the surface elements are not radial except at some intermediate position. Suppose, for example, arcs j_1 and k_1 define the inner and outer limits of vanes at the entrance plane $x=x_1$ and it is desired to construct a vane on the generated surface. If h_1 is a radial line drawn from the intersection of g_1 with arc k_1 , it is obviously desirable that the vane material should completely encompass such radial line, and similar lines in all other radial sections. With g_1 displaced only to the extent shown from a radial direction, it is obvious that this may be readily accomplished; however, if g_1 were too far displaced off center, the vane to satisfy this requirement might have to be too thick at its base. As a matter of fact, the requirement is not absolutely necessary, and if a vane is of sufficient thickness, some undercutting of radial lines through it is permissible. Under such conditions, the element g_1 at the entrance edge might well be carried further to the left to secure a still greater angular spread of each vane from inlet to outlet.

At the discharge a similar condition arises, in this case affecting the opposite face of a vane. A radial line h_2 is illustrated indicating the desirable limit of approach to an element g_2' of a vane adjacent that having elements g_1 and g_2 . The radial outlet limits j_2 and k_2 impose the limitations, and, as illustrated, if the radial extent of the outlet is small compared to that of the inlet, a correspondingly greater deviation of the element g_2 from radial condition is permissible.

As pointed out in my Patent 1,959,703, the inlet angle of a surface $x=K \tan b$ varies precisely with the radius as required for smooth pick up of fluid being handled. It will be apparent without going into mathematical proof that the surfaces here considered, by reason of close approach to $x=K_1 \tan b$ will also be, for practical purposes, completely satisfactory in this regard, particularly so when given radial entrance edges of airfoil characteristics since such edges have fairly large tolerances for entrance angles consistent with maintenance of smooth flow. However, it is also to be noted that while the improved surface is displaced from the surface $x=K_1 \tan b$ having the same value of K_1 , it will, in view of the necessary thickness of a real vane, conform to, and include, for a very considerable axial extent, a surface $x=K' \tan b$ where K' differs from K_1 . Thus it follows that real vanes of the improved type may be said to conform to a series of surfaces $x=K \tan b$ (in most practical cases to not more than three thereof) which surfaces may be considered as smoothly merging in accordance with the considerations in my application Serial No. 441,686. The advantages of the present surfaces lie primarily in their ease of generation by single cutting operations to give a large angular spacing between inlet and outlet.

The generation of real vanes of the type discussed based on the improved surfaces, results from the movement, during the generating motions indicated, of cutters of improved types along the cutter axis while it is moving in the direction PR.

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The axis of a real cutter will follow a path intermediate adjacent theoretical surfaces. In Figure 7, for example, the cutter axis in moving inwardly follows a path intersecting plane $x=x_1$ along a line l_1 , identical with g_1 but spaced therefrom half the angular spacing of adjacent elements g_1 . Likewise at plane $x=x_2$, the cutter axis traces a line l_2 midway between g_2 and g_2' . The fluid passages therefore lie along the same surfaces given by Equation 3 or 4 with the origin plane xz displaced by half the angular spacing of the vanes to az' (Figure 7). Thus both the vanes and passages conform to surfaces given by the equation.

In order that both surfaces of each passage may be simultaneously generated, the cutter is given a tapered shape which may be conical but which is most desirably substantially hyperboloidal as illustrated in Figure 8 at 64 and diagrammatically at c in Figure 7. Referring first to the latter, sections (approximately elliptical) of the cutter are shown in the two limiting planes x_1 and x_2 , to illustrate the mode of generation. As the cutter axis moves in the direction of decreasing z , the cutter is uniformly moved in a retracting direction from the blank in the direction QF (Figs. 5 and 6). Thus a part of large diameter first cuts the outermost entrance portions of the passages, and as retraction takes place, it proceeds to cut more inward parts of the entrance portions of the passages and portions further towards the discharge. Successive positions of the cutter axis are illustrated at q_1 , q_2 and q_3 . The position q_3 corresponds to the cutting of the trough of the passage.

The shape of the cutter is such that during such action the space cut, which is the envelop of the successive positions of the cutter, will be such as not to encroach (preferably) on the limiting radial lines h_1 and h_2 . If the cutter has an approximately hyperboloidal shape as illustrated, the result is to generate vanes having the desirable taper for securing sufficient strength with production of fillets where the vanes join the central portion of the disc. It will be evident that the shape of the cutter is subject to substantial variation and the hyperboloidal form may be approximated by the rotation of circular arcs or even successive straight lines about the cutter axis. The actual shape depends in each instance upon the desired vane taper and whether or not undercutting of radial lines from the vane tips is permissible. The rate of retraction of the cutter is also dependent on these same factors and related to the cutter shape, as will be obvious.

In Figure 9 there are diagrammed the factors entering into the operation of the cutter c in generating more general surfaces for vanes in accordance with Equation 2 involving adjustment p as well as n and K_2 . Assuming that the cutter has a surface of revolution which, referred to its axis and a movable point V on the cutter axis as origin, is given in cylindrical coordinates by $R^2=f(U)$, where U is measured along the axis of the cutter from the origin V , the cutter surface will be given by the following equation in terms of coordinates x, y, z , referred to the same coordinate system used above in discussing the generated surfaces:

$$6. (x_1 \cos \alpha - y_1 \sin \alpha - n \sin \alpha - p)^2 +$$

$$\left(z_1 - \frac{K_1}{\tan \alpha} + K_1 K_2 \right)^2 =$$

$$f \left(x_1 \sin \alpha + y_1 \cos \alpha + n \cos \alpha + \frac{K_3}{\tan \alpha} - K_4 \right)$$

In the above K_1 , K_2 , n , p and α are the same as previously considered. K_3 and K_4 are constants taking into account the movement of the origin point of the cutter surface along the cutter axis, i. e., the variation of the coordinate u of the origin point V. This, as evident from the description of the machine, is proportional to the movement of the point M and also to the change of z . K_3 takes into account this speed ratio while K_4 takes into account the starting position for the movement.

In accordance with the usual theory of envelopes, the surface given by Equation 6 will generate, for variations of parameter α , a surface given by eliminating the parameter α from it and its partial derivative with respect to α . Taking the partial derivative of (6) with respect to α there is obtained:

$$\begin{aligned} 7. \quad & 2K_1 \csc^2 \left(z_1 - \frac{K_1}{\tan \alpha} + K_1 K_2 \right) - \\ & 2(x_1 \cos \alpha - y_1 \sin \alpha - n \sin \alpha - p) \\ & (x_1 \sin \alpha + y_1 \cos \alpha + n \cos \alpha) = \\ & (x_1 \cos \alpha - y_1 \sin \alpha - n \sin \alpha - K_3 \csc^2 \alpha) \\ & f' \left(x_1 \sin \alpha + y_1 \cos \alpha + n \cos \alpha + \frac{K_3}{\tan \alpha} - K_4 \right) \end{aligned}$$

wherein f' is the first derivative of the function f with respect to its argument.

The solution of Equations 6 and 7 to eliminate α is laborious, even though performed graphically, but the cross-section of a passage may be thus accurately ascertained by plotting the values of x_1 , y_1 , and z_1 for a series of chosen values of α . Graphical methods of descriptive geometry are also usable involving laying out the cross-sections of the cutter in the various planes of x constant and constructing the enveloping lines thereof. It is to be noted that Equations 6 and 7 give the generated surfaces only where they are actually envelopes of the cutter surface given by $f(U)$: i. e., the troughs of the passages generated by the final position of the cutter are surfaces of revolution of this cutter position.

While the generation has been described for the most general case, it will be obvious that it is equally applicable to the special cases of having either or both of K_2 or n equal zero. If both are zero, the passages and vanes both conform strictly to $x = K_1 \tan b$. In all cases hyperboloidal, or substantially hyperboloidal cutters have been found most advantageous to secure properly shaped vanes.

In some instances, particularly where the angle between inlet and outlet measured about the axis is large, it will be found that a single generation by a cutter having a proper shape to form the desired vane taper will not suffice to give the desired trough as a part of the surface of revolution of the final cutter position. In such case recourse is had to the use of several cutters used successively and of such corresponding shapes that the proper vane shapes result from their successive operations. In each instance, however, the cutter is retracted as described for a predetermined part of the cutter action. The vane surfaces are then, except for the troughs, made up of a series of smoothly merging envelopes.

In Figures 10 and 11, there is shown a modified form of machine adapted particularly for rapid production of rotors, there being, however, less adjustability. This machine comprises a base 66 on which there is journaled about a hori-

zontal axis 70 a work support 68 on which the blank to be cut is mounted as indicated in construction lines in the two figures. Secured to the support 68 and arranged to rock the same is an arm 72 provided with a guideway 74 in which there slides the cross-head 76 pivoted at 78 to a carriage 80 which is adapted to be moved along a horizontal trackway 84 by a screw 82 driven through change speed gearing 86 from a shaft 88 connected by bevel gearing 90 to the main shaft 92 of the machine.

The main shaft 92 of the machine drives through change speed gearing 94 a transverse horizontal screw 96 which engages a nut 100 carried by a carriage 98 whereby the carriage may be moved transversely along the tracks 93. This carriage in turn supports the spindle head 102 which is guided for longitudinal movement along the track 103 so as to provide movement of the cutter 106 mounted in the spindle 104 in the direction of its axis, the cutter being driven from a motor 108 carried by 102. To secure the axial movement of the cutter, bevel gearing 110, having a splined connection with a shaft 111 driven by change speed gearing 113 from the main shaft 92, is provided to drive an upright shaft 112 mounted in the carriage 98 which in turn drives through a bevel gear 114 a second bevel gear 116 fixed against axial movement and internally threaded to engage a screw 118 secured to the head 102. By reason of the change speed gearing and connections described, it will be evident that the cutter may be given predetermined axial and transverse horizontal movements while the cross-head 76 is moved horizontally in a direction parallel to the cutter axis by the screw 82.

Comparison of the last described machine with that of Figure 1 will reveal that the two machines are identical in operation, the last named machine being essentially the former turned through 90°. It will be obvious, therefore, that the theoretical considerations involved in Figures 5, 6 and 9 fully apply to the machine of Figures 10 and 11. It may be noted that, while in this last described machine, the length of the arm MN of Figure 5 is unchangeable, nevertheless, K_1 is variable by changing the gear ratio, for example at 86, it being pointed out above that K_1 is the product of the length of MN by the ratio of the rate of movement of z to that of point M.

The machines of the type described may be utilized for the generation of turbine rotors or impellers. Turbine rotors generated thereby may take the general forms described particularly in my Patent 2,283,176. Impellers for which the machines are particularly adapted may take the general forms described in my application Serial No. 441,686, so far as axial, radial and circumferential relative dimensions are involved. The shapes of the vanes, however, are provided in accordance with what has been described above, each passage being generated by a single traverse of the cutter, though slight modifications in shape may be introduced by additional cuts for the purpose of securing thinning of vanes or other minor variations of characteristics.

Figures 12 and 13 illustrate at 120 a characteristic type of impeller producible by these mechanisms.

It may be noted that by the use of these machines, and particularly that of Figure 1, which permits wide adjustment, a complete rotor of substantial axial length containing a number of impeller or turbine wheel stages, may be cut with

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no more than axial adjustment of the blank along the support 4 in the direction of the grooves 36. Such a combination rotor may be provided by assembling a group of forgings into a single unit, as indicated, for example, in my application Serial No. 443,957, filed May 21, 1942.

What I claim and desire to protect by Letters Patent is:

1. Mechanism for the generation of elastic fluid passages in rotors comprising a rotary cutter movable in a plane with its axis constantly parallel to itself, means mounting a rotor for movement about an axis parallel to said plane of movement of said cutter axis, means for rotating said mounting about the last mentioned axis, and means relating said movements so that the axis of said cutter generates with respect to the axis of the rotor a surface having the parametric equations:

$$y = \frac{x}{\tan(\alpha + \mu)} - \frac{p}{\sin(\alpha + \mu)} - n$$

$$z = K_1 \left(\frac{1}{\tan \alpha} - K_2 \right)$$

wherein x , y and z are measured along mutually perpendicular axes, x being measured along the rotor axis and y in a direction perpendicular to the rotor axis and to the axis of rotation of said mounting.

2. Mechanism for the generation of elastic fluid passages in rotors comprising a rotary cutter movable in a plane with its axis constantly parallel to itself, means mounting a rotor for movement about an axis parallel to said plane of movement of said cutter axis, means for rotating said mounting about the last mentioned axis, and means relating said movements so that the axis of said cutter generates with respect to the axis of the rotor a surface having the parametric equations:

$$y = \frac{x}{\tan \alpha} - \frac{p}{\sin \alpha} - n$$

$$z = K_1 \left(\frac{1}{\tan \alpha} - K_2 \right)$$

wherein x , y and z are measured along mutually perpendicular axes, x being measured along the rotor axis and y in a direction perpendicular to the rotor axis and to the axis of rotation of said mounting.

3. Mechanism for the generation of elastic fluid passages in rotors comprising a rotary cutter movable in a plane with its axis constantly parallel to itself, means mounting a rotor for movement about an axis parallel to said plane of movement of said cutter axis, means for rotating said mounting about the last mentioned axis, and means relating said movements so that the axis of said cutter generates with respect to the axis of the rotor a surface having the parametric equations:

$$y = \frac{x}{\tan \alpha} - n$$

$$z = K_1 \left(\frac{1}{\tan \alpha} - K_2 \right)$$

wherein x , y and z are measured along mutually perpendicular axes, x being measured along the rotor axis and y in a direction perpendicular to the rotor axis and to the axis of rotation of said mounting.

4. Mechanism for the generation of elastic fluid passages in rotors comprising a rotary cutter movable in a plane with its axis constantly parallel

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to itself, means mounting a rotor for movement about an axis parallel to said plane of movement of said cutter axis, means for rotating said mounting about the last mentioned axis, and means relating said movements so that the axis of said cutter generates with respect to the axis of the rotor a surface having the parametric equations:

$$y = \frac{x}{\tan \alpha}$$

$$z = K_1 \left(\frac{1}{\tan \alpha} - K_2 \right)$$

wherein x , y and z are measured along mutually perpendicular axes, x being measured along the rotor axis and y in a direction perpendicular to the rotor axis and to the axis of rotation of said mounting.

5. Mechanism for the generation of elastic fluid passages in rotors comprising a rotary cutter movable in a plane with its axis constantly parallel to itself, means mounting a rotor for movement about an axis parallel to said plane of movement of said cutter axis, means for rotating said mounting about the last mentioned axis, and means relating said movements so that the axis of said cutter generates with respect to the axis of the rotor a surface having the parametric equations:

$$y = \frac{x}{\tan \alpha}$$

$$z = \frac{K_1}{\tan \alpha}$$

wherein x , y and z are measured along mutually perpendicular axes, x being measured along the rotor axis and y in a direction perpendicular to the rotor axis and to the axis of rotation of said mounting.

6. Mechanism for the generation of elastic fluid passages in rotors, said passages being separated by vanes decreasing in thickness outwardly from the rotor axis, comprising a rotary cutter movable in a plane with its axis constantly parallel to itself, means mounting a rotor for movement about an axis substantially parallel to said plane of movement of said cutter axis, means for rotating said mounting about the last mentioned axis, means for moving said cutter in the direction of its axis, and means relating said movements, said cutter having a tapered shape and arranged to cut simultaneously the major portions of the opposed vane surfaces bounding a passage.

7. Mechanism for the generation of elastic fluid passages in rotors, said passages being separated by vanes decreasing in thickness outwardly from the rotor axis, comprising a rotary cutter movable with its axis constantly parallel to itself, means mounting a rotor for movement about an axis transverse to the direction of said cutter axis, means for rotating said mounting about the last mentioned axis, means for moving said cutter in the direction of its axis, and means relating said movements, said cutter having a tapered shape and arranged to cut simultaneously the major portions of the opposed vane surfaces bounding a passage.

8. Mechanism for the generation of elastic fluid passages in rotors, said passages being separated by vanes decreasing in thickness outwardly from the rotor axis, comprising a rotary cutter movable in a plane with its axis constantly parallel to itself, means mounting a rotor for movement about an axis substantially parallel to said plane of movement of said cutter axis, means for rotating said mounting about the last mentioned axis,

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means for moving said cutter in the direction of its axis, and means relating said movements, said cutter having a tapered, approximately hyperboloidal, shape and arranged to cut simultaneously the major portions of the opposed vane surfaces bounding a passage.

9. Mechanism for the generation of elastic fluid passages in rotors, said passages being separated by vanes decreasing in thickness outwardly from the rotor axis, comprising a rotary cutter movable with its axis constantly parallel to itself, means mounting a rotor for movement about an axis transverse to the direction of said cutter axis, means for rotating said mounting about the last mentioned axis, means for moving said cutter in the direction of its axis, and means relating said movements, said cutter having a tapered, approximately hyperboloidal, shape and arranged to cut simultaneously the major portions of the opposed vane surfaces bounding a passage.

10. The method of generating elastic fluid passages in rotors comprising moving a rotary cutter with its axis substantially constantly parallel to itself, and simultaneously rotating a rotor about an axis transverse both to the rotor axis and the direction of said cutter axis.

11. The method of generating elastic fluid passages in rotors comprising moving a rotary cutter having a tapered shape in a plane with its axis substantially constantly parallel to itself, and simultaneously rotating a rotor about an axis transverse to the rotor axis and substantially parallel to said plane of movement of said cutter axis, said cutter being moved in the direction of its axis and arranged to cut simultaneously the major portions of opposed vane surfaces bounding a passage.

12. The method of generating elastic fluid passages in rotors comprising moving a rotary cutter having a tapered shape with its axis substantially constantly parallel to itself, and simultaneously rotating a rotor about an axis transverse both to

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the rotor axis and the direction of said cutter axis.

13. The method of generating elastic fluid passages in rotors comprising moving a rotary cutter having a tapered, approximately hyperboloidal, shape in a plane with its axis substantially constantly parallel to itself, and simultaneously rotating a rotor about an axis transverse to the rotor axis and substantially parallel to said plane of movement of said cutter axis, said cutter being moved in the direction of its axis and arranged to cut simultaneously the major portions of opposed vane surfaces bounding a passage.

14. The method of generating elastic fluid passages in rotors comprising moving a rotary cutter having a tapered, approximately hyperboloidal, shape with its axis substantially constantly parallel to itself, and simultaneously rotating a rotor about an axis transverse both to the rotor axis and the direction of said cutter axis.

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