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Three-dimensional Streamline Design of the Pump Flow Passage of Hydrodynamic Torque Converter

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ABSTRACT: *The design methods of three-element, centripetal turbine hydrodynamic torque converters were investigated. A new design method, three-dimensional streamline design method, was proposed. Firstly, the three-dimensional central streamline of the flow passage was designed and the streamline consists of a circular arc and a short straight line segment. After that, the central streamline equation was obtained and the design path equation was derived. Next, any other meridional flow path can numerically be obtained. Finally, the three-dimensional streamline corresponding to any meridional flow path was computed numerically. Investigation results show that the proposed method is feasible and possesses obvious advantages. First, the curvature radius of the three-dimensional central streamline remains unchanged, while any other three-dimensional streamline is close to a circular arc as well. Therefore, the energy losses caused by streamline bending can be reduced. Second, because the fluid particle near the flow passage outlet flows in a straight line law and the energy losses due to flow deviation can be reduced. Third, all the three-dimensional streamlines are theoretically located in an identical plane. Thereby energy losses caused by the turbulence can be reduced. Fourth, because of the flat blades, the manufacture cost of a torque converter can be reduced.*

Keywords: *hydrodynamic torque converter, three-dimensional streamline, curvature radius of streamline, flat blade.*

I. Introduction

A hydrodynamic torque converter is an important device used to transmit power and to improve the traction performance of a vehicle. However, an obvious disadvantage of a hydrodynamic torque converter is that its efficiency is not high enough, which will affect the economy of the vehicle.

As the flow field of a hydrodynamic torque converter is extraordinarily complex, the working mechanism of torque converters has not been understood very well. It is necessary to investigate the design theories and methods of hydrodynamic torque converters. Traditionally, one-dimensional design theory is used for the design of torque converters [1-2]. However, the flow field described by using one-dimensional theory does not entirely agree with the actual flow field of a torque converter because of too many assumptions and simplifications. Therefore, it is inevitable to introduce modeling error. After this situation taken into account, two-dimensional design theory was developed [3]. It is feasible for the two-dimensional theory to be used to describe the flow field of a centrifugal or axial-flow turbine torque converter, but the large modeling error still exists if the two-dimensional theory is used to describe the flow field of a commonly used centripetal-turbine torque converters. Actually, the flow field of a torque converter is three-dimensional, but the three-dimensional design theory is still at a exploratory stage [3-8]. Currently, one-dimensional theory is still predominant theory, and widely used methods are still the circulation distributing method and the conformal mapping method, which are based on empirical and statistical data [9]. Ref. [10] established a analytical system of research and design, Ref. [11] proposed torus streamline design method, Ref. [12] studied the streamline bending impact on energy loss, and Ref. [13] put forward a plane streamline design method. These results promote the research of design theories and design methods of torque converters.

The purpose for the investigation is to improve the efficiency of a hydrodynamic torque converter. Therefore, a new design method, three-dimensional streamline design method, is proposed in this paper.

II. Determination of 3-Dimensional Central Streamline

According to [11], construct a tangent vector at the passage inlet of the pump, as shown in Fig. 1.

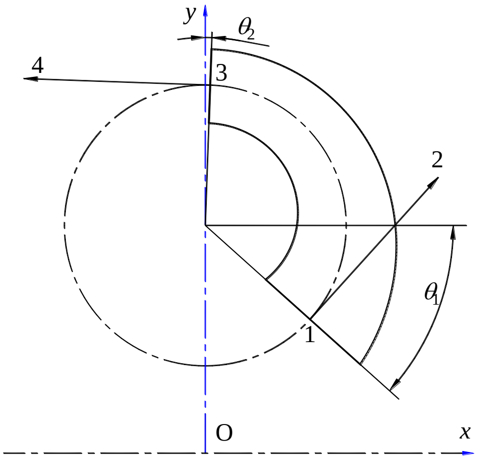

Figure 1: Tangent vectors at the pump blade inlet and outlet

The tangent vector at the passage inlet of the pump can be expressed as:

$$\mathbf{V}_{12} = (a_{12}, b_{12}, c_{12}) = (x_2 - x_1, y_2 - y_1, z_2 - z_1) \tag{1}$$

The length of the vector is:

$$L_{12} = \sqrt{a_{12}^2 + b_{12}^2 + c_{12}^2} \tag{2}$$

The tangent vector at the passage outlet is:

$$\mathbf{V}_{34} = (a_{34}, b_{34}, c_{34}) = (x_4 - x_3, y_4 - y_3, z_4 - z_3) \tag{3}$$

The length of the vector takes on L_{12} too.

Rotate tangent vector $\mathbf{V}_{34}$ an angle around x-axis to the position $3'4'$, just located in an identical plane with the vector $\mathbf{V}_{12}$. The expression of the rotation angle is:

$$\alpha = \arcsin \frac{C_2}{\sqrt{1 + C_1^2}} - \arcsin \frac{C_1}{\sqrt{1 + C_1^2}} \tag{4}$$

where

$$C_1 = \frac{(x_3 - x_2)y_1 z_4 + (x_1 - x_4)y_3 z_2 + (x_1 - x_3)(y_2 z_4 - y_4 z_2)}{(x_3 - x_2)y_1 y_4 + (x_4 - x_1)y_2 y_3 + (x_1 - x_3)(y_2 y_4 + z_2 z_4) + (x_2 - x_4)y_1 y_3} \tag{5}$$

$$C_2 = \frac{(x_3 - x_4)y_1 z_2 + (x_1 - x_2)y_3 z_4}{(x_3 - x_2)y_1 y_4 + (x_4 - x_1)y_2 y_3 + (x_1 - x_3)(y_2 y_4 + z_2 z_4) + (x_2 - x_4)y_1 y_3} \tag{6}$$

The plane determined by vector $\mathbf{V}_{12}$ .and $\mathbf{V}_{3'4'}$ equation is:

$$Ax + By + Cz = 1 \tag{7}$$

where

$$A = \frac{y_1 z_2 + (y_2 y_3 - y_1 y_3)\sin\alpha - y_3 z_2 \cos\alpha}{x_3 y_1 z_2 + (x_1 y_2 y_3 - x_2 y_1 y_3)\sin\alpha - x_1 y_3 z_2 \cos\alpha} \tag{8}$$

$$B = \frac{(x_3 z_2 - x_1 z_2) + (x_1 y_3 - x_2 y_3)\sin\alpha}{x_3 y_1 z_2 + (x_1 y_2 y_3 - x_2 y_1 y_3)\sin\alpha - x_1 y_3 z_2 \cos\alpha} \tag{9}$$

$$C = \frac{(x_3 y_1 - x_2 y_1 + x_1 y_2 - x_3 y_2) + (x_2 y_3 - x_1 y_3)\cos\alpha}{x_3 y_1 z_2 + (x_1 y_2 y_3 - x_2 y_1 y_3)\sin\alpha - x_1 y_3 z_2 \cos\alpha} \tag{10}$$

With the plane, it is convenient to design three-dimensional streamlines.

After rotation, the tangent vector at the passage outlet of the pump becomes:

$$\mathbf{V}_{3'4'} = (a_{3'4'}, b_{3'4'}, c_{3'4'}) = (x_{4'} - x_{3'}, y_{4'} - y_{3'}, z_{4'} - z_{3'}) \tag{11}$$

Construct the third vector from point 1 to point $3'$. The vector can be expressed as:

$$\mathbf{V}_{13'} = (a_{13'}, b_{13'}, c_{13'}) = (x_{3'} - x_1, y_{3'} - y_1, z_{3'} - z_1) \tag{12}$$

The length of the vector is:

$$L_{13'} = \sqrt{(x_{3'} - x_1)^2 + (y_{3'} - y_1)^2 + (z_{3'} - z_1)^2} \tag{13}$$

By using the dot product of two vectors and their lengths, the angle between vector $\mathbf{V}_{12}$ and vector $\mathbf{V}_{13'}$ can be obtained:

$$\alpha_1 = \arccos \frac{a_{12}a_{13'} + b_{12}b_{13'} + c_{12}c_{13'}}{L_{12}L_{13'}} \tag{14}$$

Similarly, the angle between vector $\mathbf{V}_{3'4'}$ and $\mathbf{V}_{13'}$ is:

$$\alpha_2 = \arccos \frac{a_{3'4'}(-a_{13'}) + b_{3'4'}(-b_{13'}) + c_{3'4'}(-c_{13'})}{L_{12}L_{13'}} \tag{15}$$

With α_1, α_2 and $L_{13'}$, a triangle $\Delta 13'5$ determined by the three parameters can be drawn, as shown in Fig. 2.

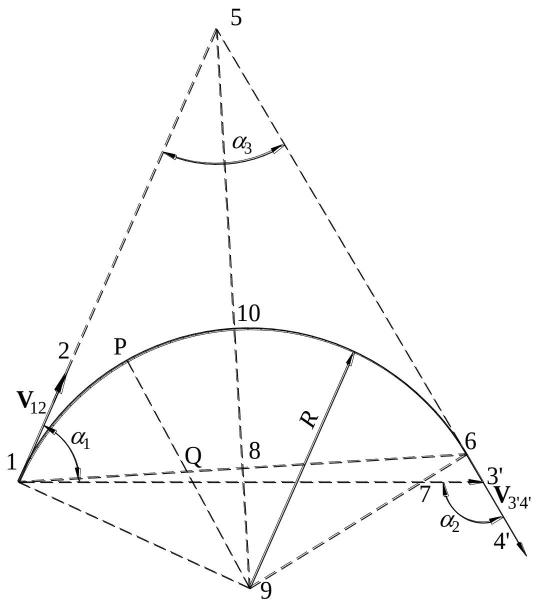

Figure 2: Triangle determined by α_1, α_2 and $L_{13'}$

From Fig. 2, it can be seen that point 5 is the intersection point of extended lines of vector $\mathbf{V}_{12}$ and $\mathbf{V}_{3'4'}$, while the angle between vector $\mathbf{V}_{12}$ and $\mathbf{V}_{3'4'}$ is $\alpha_3 = \alpha_2 - \alpha_1$. On the other hand, it can be noted that the length of straight line segment $\overline{15}$ is not equal to the length of straight line segment $\overline{3'5}$ generally.

In order to make the curvature radius of the three-dimensional central streamline reach its maximum, the three-dimensional streamline should consist of a circular arc and a straight line segment.

According to sine theorem, the length of straight line segment $\overline{15}$ is:

$$L_{15} = \frac{\sin(\pi - \alpha_2)}{\sin \alpha_3} L_{13'} \tag{16}$$

The length of straight line segment $\overline{3'5}$ is

$$L_{3'5} = \frac{\sin \alpha_1}{\sin \alpha_3} L_{13'} \tag{17}$$

The length of straight line segment $\overline{3'6}$ is

$$L_{3'6} = L_{3'5} - L_{15} \tag{18}$$

Construct auxiliary line segment $\overline{19}$ which is perpendicular to $\overline{15}$. In addition, construct auxiliary line segment $\overline{69}$ perpendicular to $\overline{65}$. Point 9 is the circular arc center of three-dimensional central streamline. The circular arc radius of the three-dimensional central streamline is:

$$R = L_{15} \tan \frac{\alpha_3}{2} \tag{19}$$

The coordinates of point 5 are:

$$\begin{cases} x_5 = x_1 + (L_{15} / L_{12})(x_2 - x_1) \\ y_5 = y_1 + (L_{15} / L_{12})(y_2 - y_1) \\ z_5 = z_1 + (L_{15} / L_{12})(z_2 - z_1) \end{cases} \tag{20}$$

The coordinates of point 6 are:

$$\begin{cases} x_6 = x_{3'} + (L_{3'6} / L_{3'5})(x_5 - x_{3'}) \\ y_6 = y_{3'} + (L_{3'6} / L_{3'5})(y_5 - y_{3'}) \\ z_6 = z_{3'} + (L_{3'6} / L_{3'5})(z_5 - z_{3'}) \end{cases} \tag{21}$$

Construct auxiliary line segment $\overline{16}$. The middle point coordinates of the auxiliary segment line $\overline{16}$ are:

$$\begin{cases} x_8 = (x_1 + x_6) / 2 \\ y_8 = (y_1 + y_6) / 2 \\ z_8 = (z_1 + z_6) / 2 \end{cases} \tag{22}$$

Construct auxiliary line $\overline{59}$. Its length is:

$$|\overline{59}| = |\overline{15}| / \cos(\alpha_3 / 2) = |\overline{58}| / \cos^2(\alpha_3 / 2) \tag{23}$$

Consequently, the circular arc center coordinates of thee-dimensional central streamline arc are:

$$\begin{cases} a = x_5 + (x_8 - x_5) / \cos^2(\alpha_3 / 2) \\ b = y_5 + (y_8 - y_5) / \cos^2(\alpha_3 / 2) \\ c = z_5 + (z_8 - z_5) / \cos^2(\alpha_3 / 2) \end{cases} \tag{24}$$

The three-dimensional circular arc can be regarded as the intersection line of a sphere and a plane. Thus, the arc equation of three-dimensional central streamline can be expressed as:

$$\begin{cases} (x-a)^2 + (y-b)^2 + (z-c)^2 = R^2 \\ Ax + By + Cz = 1 \end{cases} \tag{25}$$

For the short straight line segment $\overline{3'6}$ near the passage outlet, the equation of three-dimensional central streamline takes the form of:

$$\frac{x - x_{3'}}{x_6 - x_{3'}} = \frac{y - y_{3'}}{y_6 - y_{3'}} = \frac{z - z_{3'}}{z_6 - z_{3'}} \tag{26}$$

III. Equation of Design Path

The design path reflects the correlation between revolution radius *r* and *x*-coordinate. The three-dimensional central streamline equation can be used to derive design path equation.

3.1 Rectangular coordinate equation of design path

Expanding the first formula of (25), we can obtain:

$$\begin{cases} 2by + 2cz = (x-a)^2 + r^2 + e \\ By + Cz = 1 - Ax \end{cases} \tag{27}$$

where $e = b^2 + c^2 - R^2$

The above Simultaneous equations solved by using Cramer's rule, determinants are:

$$\Delta = 2(Cb - Bc) \tag{28}$$

$$\Delta_1 = C[(x-a)^2 + r^2 + e] - 2c(1 - Ax) \tag{29}$$

$$\Delta_2 = 2b(1 - Ax) - B[(x-a)^2 + r^2 + e] \tag{30}$$

Therefore, the solution of (27) is:

$$\begin{cases} y = \dfrac{C[(x-a)^2 + r^2 + e] - 2c(1 - Ax)}{2(Cb - Bc)} \\ z = \dfrac{2b(1 - Ax) - B[(x-a)^2 + r^2 + e]}{2(Cb - Bc)} \end{cases} \tag{31}$$

The revolution radius squared is:

$$r^2 = y^2 + z^2 = [(x-a)^2 + r^2 + e]^2 / w - u(1 - Ax)[(x-a)^2 + r^2 + e] / w + v(1 - Ax)^2 / w \tag{32}$$

where $u = 4(Bb + Cc)/(B^2 + C^2)$, $v = 4(b^2 + c^2)(B^2 + C^2)$, $w = 4(Cb - Bc)^2/(B^2 + C^2)$
Thus, the rectangular coordinate equation of design path is:

$$[(x-a)^2 + r^2 + e]^2 + v(1-Ax)^2 = u(1-Ax)[(x-a)^2 + r^2 + e] + wr^2 \tag{33}$$

From the above equation, it can be found that the design path equation is a fourth degree equation expressed with an implicit function.
For the straight line segment of the three-dimensional central streamline, according to (26), we have:

$$\begin{cases} y = px + (y_{3'} - px_{3'}) \\ z = qx + (z_{3'} - qx_{3'}) \end{cases} \tag{34}$$

where $p = (y_6 - y_{3'})/(x_6 - x_{3'})$, $q = (z_6 - z_{3'})/(x_6 - x_{3'})$.
The revolution radius expression is:

$$r = \sqrt{[px + (y_{3'} - px_{3'})]^2 + [qx + (z_{3'} - qx_{3'})]^2} \tag{35}$$

From (35), it can be seen that the meridional flow path is a hyperbola if the three-dimensional streamline is a straight line segment.

3.2 Parametric equation of design path

From (33), it can be noted that the rectangular coordinate equation of the design path is substantially complex. It is inconvenient for the expression to be used for design calculation. Therefore, it is necessary to create the parametric equation of design path. Construct a straight line segment from the circle center point 9 to point P which is located on the three-dimensional circular arc. The straight line segment $\overline{9P}$ intersects with straight line segment $\overline{16}$. The coordinates of intersection point $Q(x', y', z')$ are:

$$\begin{cases} x' = x_1 + \lambda(x_6 - x_1) \\ y' = y_1 + \lambda(y_6 - y_1) \\ z' = z_1 + \lambda(z_6 - z_1) \end{cases} \tag{36}$$

where λ is a parameter, $0 \le \lambda \le 1$.
The distance from point 9 to point Q is:

$$L_{Q9} = \sqrt{(x' - a)^2 + (y' - b)^2 + (z' - c)^2} \tag{37}$$

The coordinates of point P are:

$$\begin{cases} x = a + (R/L_{Q9})(x' - a) \\ y = b + (R/L_{Q9})(y' - b) \\ z = c + (R/L_{Q9})(z' - c) \end{cases} \tag{38}$$

Thus, we have:

$$r = \sqrt{\left[b + (R/L_{Q9})(y' - b)\right]^2 + \left[c + (R/L_{Q9})(z' - c)\right]^2} \tag{39}$$

For the straight line segment of the three- dimensional streamline, let:

$$\frac{x - x_{3'}}{x_6 - x_{3'}} = \frac{y - y_{3'}}{y_6 - y_{3'}} = \frac{z - z_{3'}}{z_6 - z_{3'}} = \lambda \tag{40}$$

Rewrite the above expression, there resulting:

$$\begin{cases} x = x_{3'} + \lambda(x_6 - x_{3'}) \\ r = \sqrt{[y_{3'} + \lambda(y_6 - y_{3'})]^2 + [z_{3'} + \lambda(z_6 - z_{3'})]^2} \end{cases} \tag{41}$$

IV. Calculation of Other Meridional Flow Paths

With the equation of design path, it is possible to calculate the coordinates of other meridional flow paths.

4.1 Numerical calculation of outer wall contour line Let:

$$F(x,r) = [(x-a)^2 + r^2 + e]^2 + v(1-Ax)^2 - u(1-Ax)[(x-a)^2 + r^2 + e] - wr^2 = 0 \tag{42}$$

Then, the two partial derivatives are:

$$F_x = [4(x-a)+Au][(x-a)^2+r^2+e]-2[u(x-a)+Av](1-Ax) \tag{43}$$

$$F_r = \{4[(x-a)^2+r^2+e]-2u(1-Ax)-2w\}r \tag{44}$$

The derivative of revolution radius with respect to *x*-coordinate is:

$$r' = -F_x / F_r \tag{45}$$

For the straight line segment of the three-dimensional central streamline, differentiating (35), we have:

$$r' = [(p^2+q^2)(x-x_{3'})+py_{3'}+qz_{3'}]/r \tag{46}$$

With the derivative r', the normal line slope of design path is:

$$k = -1/r' \tag{47}$$

The angle between the normal line and *x* axis is:

$$\gamma = \arctan k \tag{48}$$

The correlation between outer wall contour line and design path is shown in Fig. 3.

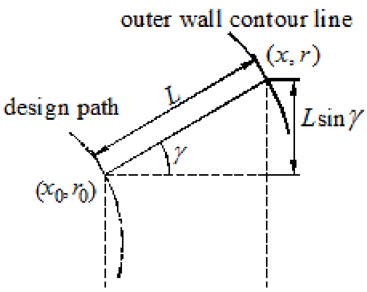

Figure 3: Correlation between design path and outer wall contour line

The spacing between design path and outer wall contour line is the a half of the flow passage. Let *L* denote the spacing. By using the lateral area formula of a right truncated cone, the correlation between design path and out wall contour line can be established:

$$\pi(2r_0 + L\sin\gamma)L = A/2 \tag{49}$$

Simplifying the above expression, we can obtain a quadric equation:

$$(\sin\gamma)L^2 + 2r_0L - A/(2\pi) = 0 \tag{50}$$

Solving the equation, we can obtain the spacing:

$$L = \frac{-2r_0 + \sqrt{(2r_0)^2 + 4(\sin\gamma)A/(2\pi)}}{2\sin\gamma} = \frac{A/(2\pi)}{r_0 + \sqrt{r_0^2 + (\sin\gamma)A/(2\pi)}} \tag{51}$$

With a given point (x_0, r_0) located on the design path, normal direction angle γ through the point, and the flow passage spacing *L*, the coordinates of the point located on the outer contour line can be obtained:

$$\begin{cases} x = x_0 + L\cos\gamma \\ r = r_0 + L\sin\gamma \end{cases} \tag{52}$$

4.2 Numerical calculation of inner wall contour line

Similarly reasoning, the *x* and *r*-coordinate of inner wall contour line can be obtained:

$$\begin{cases} x = x_0 - L\cos\gamma \\ r = r_0 - L\sin\gamma \end{cases} \tag{53}$$

4.3 General formula of meridional flow paths

Equation (52) compared with (53), it can be found that the two equations are similar. If a parameter ξ is introduced, a universal expression can be obtained:

$$\begin{cases} x = x_0 + \xi L\cos\gamma \\ r = r_0 + \xi L\sin\gamma \end{cases} \tag{54}$$

From (54), the follows can be found:

If $\xi = 0$, point (x, r) represents the point located on the design path; if $\xi = -1$, point (x, r) denotes the point located on the inner wall; if $\xi = 1$, point (x, r) is the point located on the outer wall.

Obviously, parameter ξ can take on any real number ranging from -1 to 1. That is to say, Equation (54) can be used to express any meridional flow path. Fig. 4 illustrates the meridional flow path drawn according to (54).

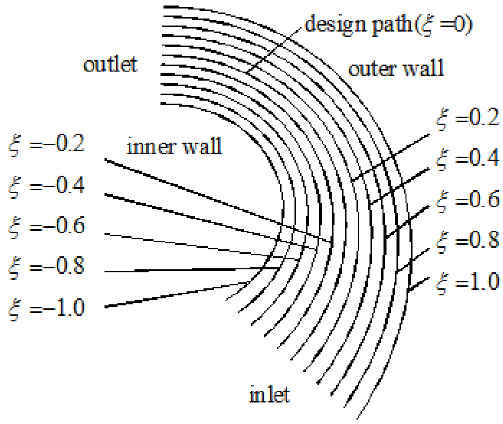

Figure 4: Meridional flow path of pump flow passage

V. Computation of Three-Dimensional Streamline Coordinates From Given Meridional Flow Path Coordinates

For a given point (x, r) located on a meridional flow path, according to the plane equation as well as the correlation between revolution radius and coordinates, there results:

$$\begin{cases} By + Cz = 1 - Ax \\ y^2 + z^2 = r^2 \end{cases} \tag{55}$$

The second expression of (55) is equivalent to:

$$\begin{cases} y = r\cos\phi \\ z = r\sin\phi \end{cases} \tag{56}$$

Equation (56) substituted into the first expression of (55), a transcendental equation can be obtained:

$$\sin\phi + (B/C)\cos\phi = (1 - Ax)/(Cr) \tag{57}$$

The solution of the equation is:

$$\phi = \arcsin\frac{(1-Ax)/r}{\sqrt{B^2+C^2}} - \arcsin\frac{B}{\sqrt{B^2+C^2}} \tag{58}$$

With angle ϕ, the y and z-coordinate of three-dimensional streamline can be obtained. In a numerical manner, the three-dimensional streamlines of the pump flow passage can be drawn, as shown in Fig. 5.

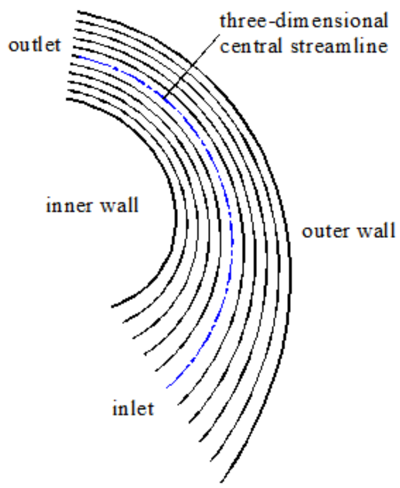

Figure 5: Three-dimensional streamlines of pump flow passage

From Fig. 5, it can be clearly seen that each three-dimensional central streamline consists of a circular arc and a short straight line segment, while any other three-dimensional streamline consists of a curved line and a short straight line segment. Each curved line is close to a circular arc. The streamlines of entire flow passage conform to boundaries and the curvature radii of streamlines change gradually. Therefore, this design is more reasonable and will greatly reduce the energy loss caused by streamline bending.

VI. Conclusion

The design methods of hydrodynamic torque converters were investigated, the main results are as follows:
(1) A three-dimensional streamline design method is proposed.
(2) A Fourth degree implicit function curved line and a hyperbola are used as the curved line type of design path.
(3) By using design path equation and its normal equation, on the other hand, with the help of numerical methods, the coordinates of the point located on any other meridional flow path can be obtained.
(4) According to each meridional flow path, the three-dimensional streamline is numerically calculated. The three-dimensional central streamline consists of a circular arc and a short straight line segment, while any other three-dimensional streamline consists of a curve and a short straight line segment.

Theoretical derivation and program calculation results show that three-dimensional streamline design method is feasible. The method possesses many advantages.
(1) The curvature radius of the three-dimensional central streamline reaches a maximum and remains unchanged (constant curvature). As a result, the energy loss caused by streamline bending can greatly be reduced.
(2) At the flow passage outlet, each three-dimensional streamline is a straight line segment. It is helpful to reduce the flow deviation angle. That is to say, the method can reduce the energy loss caused by flow deviation.
(3) As the fluid flows in a plane, theoretically, the flow field of a torque converter pump becomes quasi-two-dimensional flow field. Obviously, the method can reduce the strength of the turbulence. Therefore, it is beneficial to reduce the turbulence energy loss.
(4) All blades are flat, which can greatly reduce the manufacturing cost Of course, the disadvantage of the three-dimensional streamline design method is that the axial dimension of the torque converter increases slightly.

To sum up, advantages of the three-dimensional streamline design method are very outstanding. Therefore, the method is of engineering application value.

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