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Conclusions

Although there are several hydro powerhouses in the U.S. where interchangeable runners are currently being used, the potential for their use in increasing energy production at existing facilities is tremendous, particularly at sites with relatively constant but seasonal flows and heads. Two of the existing sites, at Trinity Dam (USBR), and at Pine Flat Dam (Kings River Conservation District), both in California, have runners designed for different head ranges, and a plant at Amistad Dam in Texas (International Boundary Commission) has runners designed for different flows. As utilities look at their older plants with thoughts of increasing their efficiencies, it could be worthwhile to look at the interchangeable runner option, particularly in light of new fish flow requirements which might have been imposed after the original plant was put in operation. As fewer new sites are developed, the future gains in hydro power generation could come primarily from re-powering of old installations, and using interchangeable runners could have a significant contribution to those future improvements.

THE DESIGN, ANALYSIS AND MANUFACTURING OF PICKWICK LANDING REPLACEMENT RUNNERS

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John David LeBrun**

ABSTRACT

This paper presents new computer automated techniques for the design, analysis and manufacture of Kaplan turbine blades. The techniques include: a) determination of the flow field at the entrance of the runner, b) direct fluid dynamic design of the blade, c) analyses of the flow in the runner at off design points, d) determination of the profile losses. The inlet flow field was determined using the finite element program "ANTHONY". The direct fluid dynamic design of the blade was executed using the two-dimensional singularities program "INNA". The final runner design was analyzed at off design points using the two-dimensional singularities program "ALHAL". The cavitation characteristics are included in "INNA" and "ALHAL" outputs. The profile losses were determined by the two-dimensional boundary layer program "DEBRA". The model test results of cavitation and performance characteristics agreed well with the theoretical prediction at the design point.

INTRODUCTION

This paper will present a discussion of the fluid dynamic design and analysis techniques used on the replacement runners of Units 1-4 at the Pickwick Landing Power Plant, where the original six (6) bladed Kaplan turbines were replaced with five (5) bladed Kaplan turbines. Developing replacement runners offers interesting challenges in hydraulic design and analysis. The new design must not only provide improvements in power and efficiency but be compatible with the constraints of the existing units, such as total thrust levels, runaway speed, and blade spindle torque. In most cases the wheel case, stay vanes, wicket gates and draft tube are not of optimum design and could also benefit from state of the art upgrades. However, an economic analysis will most often indicate the extent of the upgrade possible.

The design process can be divided into three (3) categories: 1) determination of the velocity at the runner inlet, 2) direct blade design, and 3) analysis of critical off-design conditions.

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INLET VELOCITY

A velocity distribution is needed to provide an accurate determination of the inlet conditions for the blade design. Only one passageway needs to be analyzed, because the flow through a wicket gate cascade is assumed periodic. A three-dimensional finite element analysis of the wicket gate passageway was performed. The analysis was conducted using the three-dimensional potential flow finite element computer program "ANTHONY" [1], a program used for analysis of rotating and non-rotating turbo-machinery components.

In order to have sufficient data, three wicket gate openings were analyzed, thus allowing for interpolation. Results of the analysis were post-processed at various flow rates to determine the velocity field between the wicket gate and runner, and integrated to obtain curves of flow rate versus average absolute velocity moment for each gate opening. Utilizing the design point and Euler turbine equation the needed inlet absolute velocity moment was determined and the gate opening for design was selected. Knowing the gate opening and assuming the runner entrance edge elevation, the inlet velocity distribution was determined for use in the direct blade design.

BLADE DESIGN

The turbine runner blades can be designed using two different approaches. One approach is the indirect design which is based on the iterative variation of the geometrical parameters of the profiles forming the blade with subsequent application of fluid dynamic analysis for determination of the velocity field. Using indirect design techniques the designer does not operate directly with fluid dynamic parameters and, therefore, the process of design is a very tedious iterative procedure which does not necessarily lead to the optimum geometry of the blade for given design conditions. Another approach is the direct fluid dynamic design which produces the flow in the runner and geometry of the profiles forming the blade according to given design conditions. Using the direct design technique the designer operates with fluid dynamic parameters which directly affect the velocity distribution around the blade profiles. The variation of these fluid dynamic parameters directly leads the designer to the optimum shape of blade for specified design conditions.

Pickwick Landing replacement runners were designed using the direct fluid dynamic design of Kaplan runner blades. The design was performed using the computer program "INNA" (see Appendix 1). The program "INNA" is based on the two-dimensional fluid dynamic design of cylindrical cascades (which form the blade) using the method of singularities. The singularities (sources/sinks and vortices) are continuously distributed along a line inside the cascade profile (the line of singularities). In order to satisfy continuity of the flow through the cascade the following condition is necessary:

$$\int_0^L q(\ell)\,d\ell = 0 \qquad (1)$$

where ℓ is the length along the line of singularities
$q(\ell)$ is the intensity of distributed sources/sinks
L is the entire length of the line of singularities

The distributed vortices have to create a desirable value of circulation, Γ around the profile:

$$\int_0^L \gamma(\ell)\,d\ell = \Gamma \qquad (2)$$

where $\gamma(\ell)$ is the intensity of distributed vortices.

The source/sink distribution determines the profile thickness distribution along the line of singularities as well as the radius of curvature of the leading edge at the stagnation point. The distributed vortices determine the profile loading (the difference in pressures between vacuum and pressure sides) along the line of singularities. The distribution of sources/sinks and vortices along the line of singularities is defined by the Betz series (see formulae A1-4 and A1-5 of Appendix 1). The selection of the coefficients for the γ distributions directly affects the cavitation characteristics and profile losses in the boundary layer. Values for the coefficients in the q-distribution are generally predetermined by the main geometrical parameters, such as the maximum thickness, its position along the line of singularities, radius of curvature of profile at leading edge, etc.

The main challenge in the design of Kaplan runners using "INNA" is to achieve the optimum balance between minimum profile losses and cavitation performance. This balance can be achieved by an iteration procedure involving variations of both the γ-distribution and geometric parameters.

The blade design for Pickwick Landing began with the initial selection of the geometric parameters based on past designs and wheel case constraints, and with the initial coefficient selection for the γ-distribution, which only has to satisfy equation [2] (for details see Appendix 1). At this point the iteration process began. The output of these parametric studies was evaluated on the basis of profile losses and cavitation performance. The profile losses were determined using the two-dimensional boundary layer program "DEBRA" [2], while the cavitation performance was evaluated from "INNA" cavitation curves (Figure 1) by comparison with plant sigma values. Once an optimum balance was achieved, a "smooth surface" was generated by adjusting the profiles about their centerline. The final blade design (Figure 2) was used to build a three-dimensional finite element model for analysis using the "ANTHONY" program in order to evaluate the three-dimensional velocity effects on the blade losses and cavitation performance.

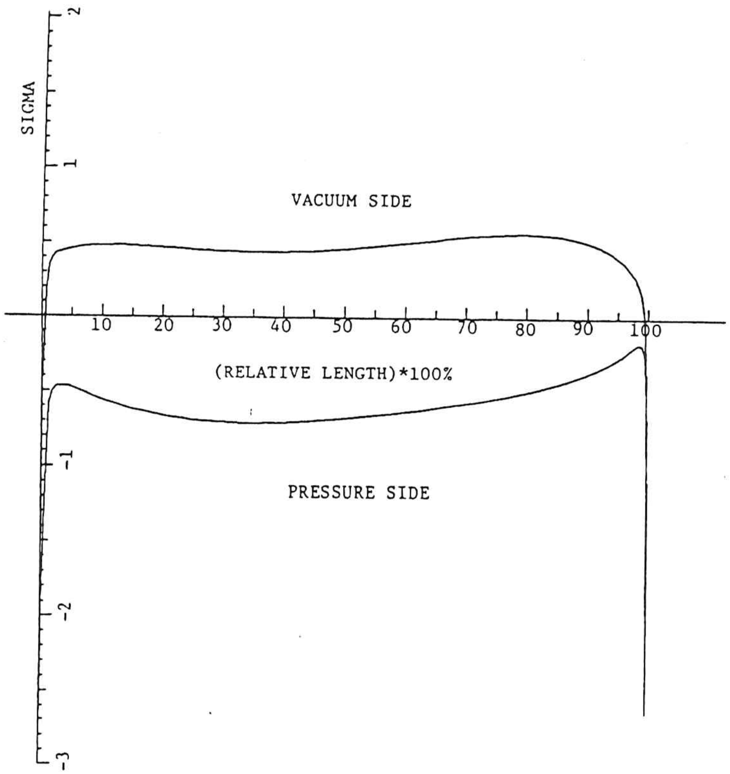

Figure 1 Sigma Distribution along the Profile.

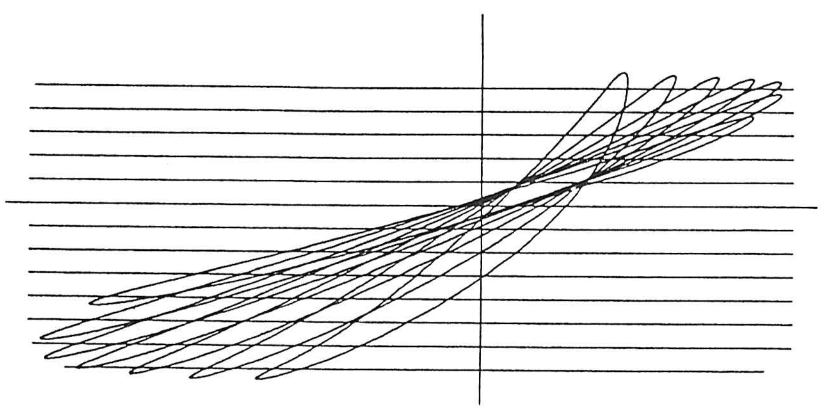

Figure 2 The Profiles of the Cylindrical Cascades.

OFF DESIGN ANALYSIS

Once the blade design was selected from the "INNA" analysis, off-design conditions were evaluated. These conditions were chosen on the basis of critical cavitation conditions. For Pickwick Landing full runner blade tilt and maximum gate opening for the following head and flow conditions were accepted:

H = 16.764m (55 ft.)
Q = 410m^3/s (14,489 ft^3/s)
σ_p = 0.95

and

H = 13.11m (43 ft.)
Q = 413m^3/s (14,584 ft^3/s)
σ_p = 1.12

Combining the above conditions and the wicket gate analysis results, the computer inputs for "ALHAL" (see Appendix 2) were generated. The plant sigma conditions were then compared with "ALHAL" results and evaluated.

If the off-design analysis indicated that cavitation performance or profile losses were unacceptable, a new design point would have to be selected and a new blade designed. The profiles of the cylindrical cascades for the final design are shown in Figure 3.

TESTING

The final blade was manufactured on a 5-axis milling machine, using the machining tapes as generated by "INNA" and tested in the Pickwick Landing homologous model. Testing was performed under the IEC test code at the S. Morgan Smith Laboratory. The testing program involved measurement of performance, cavitation, runaway speed and blade spindle torques. The results agreed well at the design points: at the design N_{11} of 148.3 the Q_{11} opt was 1.358 and Q_{11} design was 1.325; a difference of 2.5%.

At the off-design points comparisons of sigma (Thoma cavitation coefficient) tested to that predicted can be made. For an off-design head of 16.76m and maximum blade tilt and maximum gate opening, the tested σ_s was .73 and predicted σ_s was .79 (σ_s as defined by the IEC Test Code). For an off-design head of 13.11m the tested σ_s was 1.2 and predicted was 1.32.

CONCLUSION

Good agreement between the predicted values at the design point and model test results permit the following conclusion. The direct fluid dynamic method of runner design is an effective technique in determination of the optimum blade shape with regards to the balance between profile losses and cavitation performance.

APPENDIX 1, THE PROGRAM "INNA"

A.1.1 Introduction

The program "INNA" designs the geometry of the blade for given values of Q_{11} and N_{11}. The program also produces the blade geometry drawing, machining tapes and the input into boundary layer program "DEBRA". It is based on the theory of straight cascade design by the method of singularities [3] applied to each cylindrical cascade of the runner.

A.1.2 Assumptions

* The fluid is inviscid and incompressible.
** The stream surfaces of the flow in the runner are cylinders coaxial with the turbine axis ($V_r = 0$).
*** The flow in each cylindrical lamina (formed by two adjacent stream surfaces) is independent of the flow in other cylindrical laminae.
**** The radial projection of the absolute flow curl is equal to zero ($rot_r \vec{V} = 0$).

A.1.3 Given Values

* The head of turbine H, the flow rate Q, the speed of turbine shaft rotation N, the diameter of the runner D_r, the diameter of the hub D_h, and the number of blades N_b.

** The distribution of axial and circumferential projections of absolute velocity ($V_{z\infty} = V_{z\infty}(r)$ and $V_{u1} = V_{u1}(r)$) at entrance to the runner (at infinity).

*** The main geometrical parameters of the N_c cylindrical cascades of the blade (r_c - radius of cascade, ℓ/t - solidity, h_m - maximum relative thickness of the profile and x_m - the position of maximum thickness, etc.).

**** The relative values of coefficients for vortex distribution (A_i) along the line of singularities (see formula (A1-5)).

A.1.4 Values to be Determined

* The complete geometry of the blade profiles for each cylindrical section (including the coordinates of stagnation points at entrance and exit).

** The distributions around the cylindrical section profile of the relative velocity magnitude ($W = W(\ell)$, where ℓ is the length along the profile) and of cavitation coefficient ($\sigma = \sigma(\ell)$) on both vacuum and pressure sides.

A.1.5 The Theory of the Solution

According to the assumption *** each cascade of profiles forming the blade is calculated separately.

The circulation around the profile of a straight cascade is:

$$\Gamma = T\,(W_{u1} - W_{u2}) \qquad \text{(A1-1)}$$

where $T = \dfrac{2\pi r_c}{N_b}$ is cascade spacing

$W_u = V_u - \omega r_c$ is circumferential projection of relative velocity

Now applying Euler Equation

$$(V_{u1} - V_{u2})\, r_c = \frac{gH\eta}{\omega} \qquad \text{(A1-2)}$$

one obtains

$$\Gamma = \frac{2\pi}{N_b}\,\frac{\eta H g}{\omega} \qquad \text{(A1-3)}$$

In order to obtain the profile of the straight cascade having desirable value of circulation for given flow at entrance and having desirable geometrical features (maximum thickness h_m position of maximum thickness x_m, radius of leading edge ρ_ℓ, etc.), the singularities (vortices, sources and sinks) are distributed along the line of singularities located inside of the future profile.

The vortices are distributed by Betz series with six terms [3].

$$\gamma(x) = \left(A_o \left(\frac{1+x}{1-x}\right)^{0.5} + (1-x^2)^{0.5} \sum_{n=1}^{5} A_n x^{n-1}\right. \qquad \text{(A1-4)}$$

$x = \ell/0.5L$, $[-1 \leq x \leq 1]$

where ℓ is length along the line of singularities from the midpoint

L is the length of the line of singularities

Integrating (A1-4) along the line of singularities

one obtains the equation connecting Γ with coefficients $A_o, A_1, \ldots, A_5$

$$\Gamma = \frac{\pi L}{2} (A_o + \frac{1}{2} A_1 + \frac{1}{8} A_3 + \frac{1}{16} A_5) \qquad (A1-5)$$

Using relative values for A-coefficients from input and the equation (A1-5) the program finds the absolute values for the coefficients. It is clear from (A1-5) that the coefficients A_2 and A_4 can be accepted arbitrarily without any regard to the value of Γ.

The significant difference between the program INNA and other solutions for the same problem is that the same A-coefficients are accepted for the all cylindrical cascades of the runner. The reason for that is to organize in three-dimensional space the closest to radial system of vortex filaments along the surface formed by the lines of singularities of all cascades.

As it was shown by Dr. L. Simonov [4] in the case of radial vortex filaments the flow computed by intrinsic three-dimensional solution and by two-dimensional solution (based on assumption ***) are very close.

The sources and sinks are distributed also by Betz series as it was accepted by I. Etinberg [5], but instead of five terms we use seven:

$$q(x) = B_0\left(\frac{1+x}{1-x}\right)^{0.5} + (1-x^2)\sum_{n=1}^{5} B_n x^{n-1} + B_{-0}\left(\frac{1-x}{1+x}\right)^{0.5} \qquad (A1-6)$$

And since

$$\int_{-1}^{1} q(x)dx = 0 \qquad (A1-7)$$

The first equation for determination of B - coefficients is:

$$B_0 + B_{-0} + \frac{1}{2} B_1 + \frac{1}{8} B_3 + \frac{1}{16} B_5 = 0 \qquad (A1-8)$$

The other six equations for B-coefficients ~~determination~~ are satisfying the geometrical parameters of the profile (h_m, x_m, etc.). The presence of two additional terms in (A1-6) gives the possibility to satisfy additionally specified geometrical parameters in comparison with [5].

It is clear that the B-coefficients are different for the different cylindrical cascades in the runner since the profiles of these cascades have different geometrical features.

After determination of A and B coefficients the geometry of the line of singularities is obtained using the method of iterations. The condition for the line of singularities computation is based on the criterion for existance of the closed streamline (the future profile) around the line of singularities. The stagnation points at entrance and exit are computed using the same technique as in [3].

When the line of singularities and the stagnation points are established, the program determines geometry of the vacuum and the pressure sides of profile (using Gauss Theorem) and computes the velocity distribution along both sides of profile.

APPENDIX 2, THE PROGRAM "ALHAL"

A.2.1 Introduction

The program "ALHAL" finds the flow around the blades in the regimes different from the design regime. It is based on an analysis of the flow through two-dimensional straight cascades. The geometry of these two-dimensional cascades is a result of the intersection of cylindrical stream surfaces with the three-dimensional cascade of the runner blades. In "ALHAL" the flow analysis in the straight cascade is performed by a subroutine based on the program "NEUMASC" [6].

A.2.2 Assumptions

The assumptions for ALHAL are the same as for INNA (see A.1.2).

A.2.3 Given Values

* The head of turbine H, the speed of turbine shaft rotation N, the diameter of the runner D_r and the diameter of the hub D_h.

** The distributions of velocity axial projection in infinity ($V_{zs\infty} = V_{zs\infty}(r)$, where $V_{zs\infty} = V_{zs\infty}/Q$) and of angle between absolute velocity vector and axial direction at entrance in infinity ($\beta_I = \beta_I(r)$).

*** The geometry of the sufficient number N_c of the cylindrical sections of the blade and the number of the blades N_b.

A.2.4 Values to be Determined

* Flow rate Q.

** The distributions around the cylindrical section (profile) of the relative velocity magnitude ($W = W(x)$, where x is the length along the profile chord) of cavitation coefficient ($\sigma = \sigma(x)$) and of the pressure ($p = p(x)$), on both vacuum and pressure sides.

*** The hydraulic axial force produced by the runner blades (the thrust force of the runner blades).

**** The hydraulic torque of the blade around its spindle axis.

A.2.5 The Theory of the Solution

The solution is based on well known kinematic relationship for the straight cascade [4]:

$$\tan\alpha_E = A\tan\alpha_I + B \qquad \text{(A2-1)}$$

where α_I and α_E are the angles of relative velocity vector with axial direction at inlet and exit correspondingly.

In (A2-1) A and B are the constants which strictly depend on the geometry of the straight cascade. In order to find the constants A and B for one cascade (cylindrical section) the subroutine NEUMASC finds the values of α_E for two different arbitrary values of α_I. When the values of components A and B are found for each cascade, the value of the flow rate Q can be determined using Euler equation.

The Euler equation for axial flow runner is:

$$\int_{r_h}^{r_r} 2\pi(V_{uI} - V_{uE})\, V_{z\infty} r^2 dr = \frac{g\eta HQ}{\omega} \qquad \text{(A2-2)}$$

where V_{uI} and V_{uE} are the circumferential projection of absolute velocity at inlet and exit correspondingly. $V_{z\infty}$ is the axial projection of absolute velocity.

$\omega = \frac{\pi N}{30}$ is angular velocity

r_r and r_h are the radii of the runner and the hub correspondingly.

Combining (A2-1) and (A2-2) one obtains the equation for computation of Q:

$$QI_1 + \omega I_2 = \frac{g\eta H}{2\pi\omega} \qquad \text{(A2-3)}$$

where

$$I_1 = \int_{r_h}^{r_r} V^2_{zs\infty} [\tan\beta_I (1 - A) - B]\, r^2 dr$$

$$I_2 = \int_{r_h}^{r_r} (A - 1) V_{zs\infty} r^3 dr$$

Knowing Q the values of α_I for each cascade can be determined and, therefore, the velocity field around the cylindrical sections of the blade. The flow field yields the cavitation coefficient distribution for the runner computed by the well known formula [5].

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