New Method Manufacturing of Control Rod Wing For Nuclear Reactor 45.7 MW

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Abstrak

Menggunakan pendekatan kuantum, metoda optimasi bentuk sayap batang kendali nuklir berdasarkan teori kontrol pada struktur nuklir secara intensif dikembangkan khususnya di reaktor nuklir riset Canadian Deuterium Uranium (CANDU). Batang kendali yang memiliki panjang 5 meter, diameter 0,80 meter dan ketebalan 0,10 meter mempunyai sayap untuk pengendalian reaksi neutron termal saat muncul radiasi Cerenkov. Bergerak secara normal dengan kecepatan 76 mm/detik. Mengalirnya arus partikel υ pada fluks neutron termal sebesar 2,1 x 10^5 currie/mm merupakan masalah tersendiri dalam pembuatan sayap batang kendali nuklir tersebut. Berlandaskan pendekatan kuantum pada teori kontrol rantai nuklir transuranium, maka bobot struktural dan aliran fluks neutron termal merupakan teknik optimasi terbaik pada kondisi medan magnetik 450 tesla dan daya terpasang 45,7 MW. Tujuan riset ini adalah mengusulkan bentuk sayap batang kendali nuklir yang baru melalui rangkaian perumusan matematis yang dimodelkan dengan persamaan Euler dan pembuatan miniatur sayap batang kendali, maka sudut yang dapat diharapkan sebesar antara $37,6^0$ sampai $42,1^0$ dengan berbasiskan matriks Sr_2O sebagai material utama dan muatan DUO_2 adalah ruang reaksi nuklir yang ada.

***Kata kunci :** Sayap batang kendali, pendekatan kuantum, persamaan Euler*

Abstract

Using the quantum approaching, the nuclear control rod wing shape optimization method based on control theory in nuclear structure have been intensively developed especially in Canadian Deuterium Uranium (CANDU) nuclear research reactor. The control rod blade dimensions include 5 meters length, 0.80 meters diameter, and 0.10 meters thickness and it has the wing for thermal neutron reaction controlling at the Cerenkov's radiation coming up. Moving on normally with 76 mm/second velocity. The floating of υ particle in 2.1 x 10^5 currie/mm thermal neutron flux is one problem in nuclear control rod wing manufacturing. Based on quantum approaching in transuranium nuclear chain control theory, the structural and thermal neutron flux flow is the best optimization technique for 450 tesla magnetic field weight and 45.7 MW adjusted power. This research purposed for new shape of nuclear control rod wing by several mathematical formulations have been modeled by Euler equations and build the miniature of control rod wing, then the angle has expected around 37.6^0 until 42.1^0 based on Sr_2O matrix as the primer material and DUO_2 loading is the nuclear chamber.

***Keywords :** control rod wing, quantum approaching, Euler equations*

1. Introduction

While. quantum approaching methods based on nuclear DUO_2 reaction are now well established, quite accurate, and robust, the ultimate need in the design process is to find the optimum shape which maximizes the control rod wing performance. One way to approach this objective is to view it as a control problem, in which the wing is treated as a device which controls the neutron flow to produce lift with minimum drag, while meeting other requirements such as low structural weight, sufficient neutron flux volume, and stability and control constraints. The control rod dimensions include 5 meters length, 0.80 meters diameter, and 0.10 meters thickness. Moving on normally with 76 mm/second speed (CANDU, 2003)

In this paper, apply the theory of optimal control of systems governed by partial differential equations with boundary control (Scott and Harding, 2004) and by experimental research at Canadian Deuterium Uranium (CANDU) by Magnetic Stirrer and Catch-Nuc equipments, then we have proposed a new shape for nuclear control rod wing, in this case through changing the shape of the boundary. Using this theory, can find the Frechet derivative (infinitely dimensional gradient) of the neutron flux function with respect to the shape by solving an adjoint problem, and then we make an improvement by making a modification in a descent direction.

Control rod wing plan form modification can yield large improvement in wing performance but can also affect wing angle and stability and control issues. It is well known that the induced drag varies inversely with the square of the span. Hence the induced drag can be reduce by increasing the span. Moreover, shock drag in transuranium flow might be reduced by increasing sweepback or increasing the chord to reduce the thickness to chord ratio (Duprix, 2003). However, thermal neutron optimization may lead to highly suspect result because the decrease in drag might come at the expense of the increase in control rod wing angle. Therefore it is essential to account for the effect of plan form change on wing weight. Also, for practical design purposes, a fast and accurate method to predict the wing angle and its gradient is necessary.

Our previous work validates a design methodology form control rod wing plan form optimization with simple estimation of wing weight. We find that if the nuclear structure function contains both thermal neutron flux and structural weight dependencies, the trade-off between these two dependencies will lead to a useful design. However, this raises the question of how to properly integrate these dependencies together. One practical way to solve the relative importance of thermal neutron flux and structural dependencies is to consider the overall design, such as the maximum range of the control rod wing.

In this research, has reported improvements in the estimation of control rod wing angle, using a new structural weight model that is sensitive to changes to both geometry and nuclear structure load. Because the coupling between this wing geometry and nuclear structure load, in order to reduce computational time, extend the adjoint method to calculate the wing angle gradient with respect to planform variations.

We also consider an alternative approach of how to combine the thermal neutron flux floating and structural functions to cover a broader range.

2. Literature Review

In this work the equation of steady flow for thermal neutron flux without υ particle and using the quantum approaching formulations

$$\frac{\partial}{\partial \chi_i} f_i(\omega) = 0 \qquad (1)$$

where ω is the solution vector, and $f_i(\omega)$ are the flux vector along the χ_i axis are applied in a fixed computational domain, with coordinates ξ_i, so that

$$R(\omega,S)=\frac{\partial}{\partial \xi_i}F_i(\omega)$$
$$=\frac{\partial}{\partial \xi_i}S_{ij}\ f_j(\omega)=0 \quad (2)$$

where S_{ij} are the coefficients of the Jacobian matrix of the transformation. Then geometry changes are represented by changes δS_{ij} in the metric coefficients. Suppose one wishes to minimize the thermal neutron flux function of a boundary integral using by approximation calculation with Magnetic Stirrer equipment

$$I=\int_B M(\omega,S)\,dB_\xi + \int_B N(\omega,S)\,dB_\xi \quad (3)$$

where the integral of $M(\omega,S)$ could be a thermal neutron flux function, and the integral of $N(\omega,S)$ could be a structural function, e.g. control rod wing angle. Then one can augment the nuclear structure function through Langrange multiplier ψ (Pal, 2000) as

$$I=\int_B M(\omega,S)\,dB_\xi + \int_D \psi^T\,\Re(\omega,S)\,dD_\xi + \int_B N(\omega,S)\,d\,B_\xi \quad (4)$$

A shape variation δS causes a variation

$$\delta I=\int_B \delta M\ dB_\xi + \int_D \psi^T\frac{\partial}{\partial \xi_i}\delta F_i\ dD_\xi + \int_B \delta N\ dB_\xi \quad (5)$$

The second term can be integrated by parts to give

$$\int_B n_i\psi^T\delta F_i dB_\varepsilon - \int_D \frac{\partial \psi^T}{\partial \varepsilon_i}\delta F_i dD_\varepsilon \quad (6)$$

Now, choosing ψ to satisfy the adjoint equation

$$\left(S_{ij}\frac{\partial f_j}{\partial w}\right)^T\frac{\partial \psi}{\partial \varepsilon_i}=0 \quad (7)$$

with appropriate boundary conditions

$$n_i\,\psi^T S_{ij}\,f_{jw}=M_w+N_w,$$

where

$$M_w=\frac{\partial M}{\partial w},\ and \qquad N_w=\frac{\partial N}{\partial w}, \quad (8)$$

the explicit dependence on δw is eliminated, allowing the neutron variations to be expressed in terms of δS and the adjoint solution, and hence finally in terms of the change δF in a function $F(\varepsilon)$ defining the shape.

Thus one obtains

$$\delta I=\int G\delta F\ d\varepsilon=\langle G,\delta F\rangle \quad (9)$$

where G is the infinite dimensional gradient (Frechet derivative) at the nuclear structure of one flow and adjoint solution. Then one can make an improvement by setting

$$\delta F=-\lambda G \quad (10)$$

In fact the gradient G is generally of a lower smoothness class than the shape F. Hence it is important to restore the smoothness. This may be effected by passing to a weighted Sobolev (Russell, 2001) inner product of the form

$$\langle u,\upsilon\rangle=\int\left(u\upsilon+\epsilon\frac{\partial u}{\partial \xi}\frac{\partial \upsilon}{\partial \xi}\right)d\xi \quad (11)$$

This is equivalent to replacing G by $\overline{G}$, where in one dimension

$\overline{G}-\frac{\partial}{\partial\xi}\overline{G}\frac{\partial\overline{G}}{\partial\xi}=G, \overline{G}=$ zero at end points and making a shape change $\delta F=-\lambda\overline{G}$.

3. Methodology

Planform design variables

In this work, we model the wing of interest using six planform variables: root chord (c_1), mid-span chord (c_2), tip chord (c_3), span (b), sweepback (Λ), and wing thickness ratio (t), as shown in figure 1. This choice of

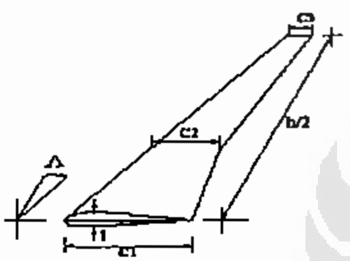

Figure 1.
Modeled wing governed by six planform variables; root chord (c_1), mid-span chord (c_2), tip chord (c_3), span (b), and sweepback (Λ), wing thickness ratio (t).
(Courtesy of CANDU nuclear research reactor, Canada)

design parameters will lead to an optimum wing shape that will not require an extensive structural analysis and can be manufactured effectively.

Nuclear Structure Function for Planform design

In order to design a high performance transonic wing based on the nuclear structure control theory, which will lead to a desired pressure distribution, and still maintain a realistic shape, the natural choice is to set

$$I=\alpha_1 C_D+\alpha_2\frac{1}{2}\int_B (p-pd)^2 dS+Cw \quad (12)$$

with

$$Cw=\frac{W_{wing}}{q\infty\, S_{ref}} \quad (13)$$

where

C_D = drag coefficient
Cw = normalized wing structural angle
P = current of neutron surface pressure,
P_d = desired pressure,
$q\infty$ = dynamic pressure,
S_{ref} = reference area,
W_{wing} = wing structural weight, and
$\alpha_1,\alpha_2,\alpha_3$ = weighting parameters for drag, inverse design, and structural weight respectively.

The constant α_2 is introduced to provide the designer some control over the pressure distribution.

Structural weight model

To estimate W_{wing} , a realistic model should account for both planform geometry and wing loading, but it should be simplified enough that we can express it as an analytical function.

An analytical model to estimate the minimal material to resist material and buckling failures has been developed by CANDU. When shear and buckling effects are small, they may be neglected, resulting in a simplified model developed by CANDU. In this paper, following the analysis developed by CANDU.

The wing structure is modeled by a structure box, whose major structural material is the box skin. The skin thickness (t_s) varies along the span and resists the bending moment caused by the wing lift. Then, the structural wing weight can be calculated based on Sr_2O material of the skin.

Consider a box structure of a swept wing whose quarter-chord swept is Λ and its cross-section A-A as shown in figures 2. The skin thickness t_s , structure box chord c_s , and overall thickness t vary along the span. The maximum normal stress from the bending moment at a section Z^* is

$$\sigma = \frac{M(z^*)}{t\, t_s\, c_s} \qquad (14)$$

The corresponding wing structural weight is

$$W_{wing}\ \alpha \int_{structual\ span} \frac{M}{t} dl$$
$$= 2 \frac{\rho_{mat} g}{\sigma \cos(\Lambda)} \int_{-\frac{b}{2}}^{\frac{b}{2}} \frac{M(z^*)}{t(z^*)} dz^* \qquad (15)$$

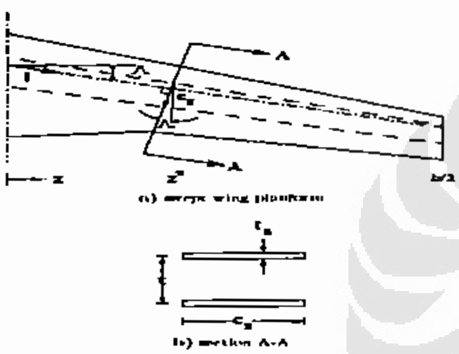

Figure 2.
Structural model for a swept control rod wing (Courtesy of CANDU nuclear research reactor, Canada)

$$= 4 \frac{\rho_{mat} g}{\sigma \cos(\Lambda)} \int_{0}^{\frac{b}{2}} \frac{M(z^*)}{t(z^*)} dz^*, \qquad (16)$$

and

$$Cw = \frac{\beta}{\cos(\Lambda)} \int_{0}^{\frac{b}{2}} \frac{M(z^*)}{t(z^*)} dz^*, \qquad (17)$$

where

$$\beta = \frac{4\, \rho_{mat}\, g}{\sigma_q \infty S_{ref}},$$

ρ_{mat} is the material density , and g is the gravitational constant.

The bending moment can be calculated by integrating pressure toward the wing tip.

$$M(z^*) = -\int_{z^*}^{\frac{b}{2}} \frac{p(x,z)(z-z^*)}{\cos(\Lambda)} dA$$
$$= -\int_{z^*}^{\frac{b}{2}} \oint_{wing} \frac{p(x,z)(z-z^*)}{\cos(\Lambda)} dxdz$$

......(18)

Thus

$$Cw = \frac{-\beta}{\cos(\Lambda)^2} \int_{0}^{\frac{b}{2}} \int_{z^*}^{\frac{b}{2}} \oint_{wing} \frac{p(x,z)(z-z^*)}{t(z^*)} dxdzdz^*$$

......(19)

To form the corresponding adjoint boundary condition (8), C_w

Must be expressed as $\int_B dB_\xi$ in the computation domain, or $\int\int dxdz$ in a physical domain to match the boundary term of (8).

To switch the order of integral of (19), introduce a Heaviside function (Duprix, 2003)

$$H(z-z^*) = \begin{cases} 0, & z < z^* \\ 1, & z > z^* \end{cases}$$

Then (6) can be rewritten as

$$Cw = \frac{-\beta}{\cos(\Lambda)}{}^{2}$$

$$\int_{0}^{\frac{b}{2}} \int_{0}^{\frac{b}{2}} \frac{p(x,z)H(z-z^*)(z-z^*)}{t(z^*)} dxdzdz^*$$

$$= \frac{-\beta}{\cos(\Lambda)^2} \int_{0}^{\frac{b}{2}} \oint_{wing} p(x,z)K(z) dxdz, \qquad (20)$$

where

$$K(z) = \int_{0}^{\frac{b}{2}} \frac{H(z-z^*)(z-z^*)}{t(z^*)} dz^*$$
$$= \int_{0}^{z} \frac{z-z^*}{t(z^*)} dz^*$$

In the computational domain,

$$Cw = \frac{-\beta}{\cos(\Lambda)^2} \oint_B p(\xi_1\, \xi_3) K(\xi_3) S_{22} d\xi_1 d\xi_3. \qquad (21)$$

and K (ξ_3) is a one-to-one mapping of *K(z)*.

4. Result and Discussions

Adjoint boundary condition for the structural weight

For simplicity, it is assumed that the portion of the boundary that undergoes shape modifications is restricted to the coordinate $\xi_2 = 0$. Then (8) may be simplified by incorporating the conditions
$n_1 = n_3 = 0,\ n_2 = 1$ and $dB\xi = d\xi_1 d\xi_3$,
so that the only variation δF_2 needs to be considered at the wall boundary. Moreover, the condition that there is no flow through the boundary at $\xi_2 = 0$ is equivalent to

$$U_2 = 0,$$

and

$$\delta U_2 = 0$$

when the boundary shape is modified. Consequently,

$$\delta F = \delta p \begin{Bmatrix} 0 \\ S_{21} \\ S_{22} \\ S_{23} \\ 0 \end{Bmatrix} + p \begin{Bmatrix} 0 \\ \delta S_{21} \\ \delta S_{22} \\ \delta S_{23} \\ 0 \end{Bmatrix} \qquad (22)$$

The variation of Cw is

$$\delta Cw = -\beta \oint_B \delta p \frac{KS_{22}}{\cos(\Lambda)^2} + p\delta\left(\frac{KS_{22}}{\cos(\Lambda)^2}\right) d\xi_1 d\xi_3 \qquad \ldots\ldots(23)$$

Since δF_2 and δCw depend only on the pressure, it allows a complete cancellation of dependency of the boundary integral on δp, and the adjoint boundary condition reduces to

$$\psi_2 S_{21} + \psi_3 S_{22} + \psi_4 S_{23} = \frac{-\beta}{\cos(\Lambda)^2} KS_{22} \qquad (24)$$

Adjustment of the adjoint boundary condition for a design with fixed C_L

A typical design problem is to find an optimum wing shape, while maintaining constant lift. A practical way to maintain the lift is to allow the angle of neutron attack to adjust at each design cycle. In such a case the variation of the nuclear structure function needs to include a variation from the change of angle of neutron attack.

If

$$I = Cw$$

then

$$\delta I = \bar{\delta} Cw + \frac{\partial Cw}{\partial \alpha} \delta \alpha \qquad (25)$$

where $\bar{\delta}$ refers to variations independent of changes in α. For fixed lift,

$$\begin{aligned} \delta C_L &= 0 \\ &= \delta[C_N \cos(\alpha) - C_A \sin(\alpha)] \\ &= \bar{\delta} C_N \cos(\alpha) - \bar{\delta} C_A \sin(\alpha) \\ &\quad + \left[\frac{\partial C_N}{\partial \alpha}\cos(\alpha) - \frac{\partial C_A}{\partial \alpha}\sin(\alpha)\right]\delta\alpha \\ &\quad + [-C_N \sin(\alpha) - C_A \cos(\alpha)]\delta\alpha. \end{aligned} \qquad (26)$$

leaving

$$\begin{aligned} \delta\alpha &= \frac{-\tilde{\delta} C_N \cos(\alpha) + \tilde{\delta} C_A \sin(\alpha)}{-CD + \frac{\partial C_N}{\partial \alpha}\cos(\alpha) - \frac{\partial C_A}{\partial \alpha}\sin(\alpha)} \\ &= \frac{-\tilde{\delta} C_N \cos(\alpha) + \delta C_A \cos(\alpha)}{\frac{\partial C_L}{\partial \alpha}} \end{aligned} \qquad (27)$$

Combining (25) and (27), and using

$$\frac{\frac{\partial C_w}{\partial \alpha}}{\frac{\partial C_L}{\partial \alpha}} = \frac{\partial C_W}{\partial C_L},$$

(25) becomes

$$\delta I = \tilde{\delta}C_w + \frac{\partial C_w}{\partial C_L}\left(-\tilde{\delta}C_N \cos(\alpha) + \tilde{\delta}C_A \sin(\alpha)\right) \quad \ldots\ldots(28)$$

To calculate $\frac{\partial C_W}{\partial C_L}$, an outer iteration needs to be incorporated with the thermal neutron flow solver which changes α.

To express the corresponding adjoint boundary condition, recall

$$C_N = \frac{-1}{q\infty S_{ref}} \int_B p S_{22}\, d\xi_1\, d\xi_3 \qquad (29)$$

$$C_A = \frac{-1}{q\infty S_{ref}} \int_B p S_{21}\, d\xi_1\, d\xi_3 \qquad (30)$$

Following the procedure outlined in the previous section, equations (28), (29), and (30) can be combined with the variation of the thermal neutron flow equations and equations (24) will be modified to

$$\psi_2 S_{21} + \psi_3 S_{22} + \psi_4 S_{23} = \frac{-\beta}{\cos(\Lambda)^2} K S_{22} - \gamma \sin(\alpha) S_{21} + \gamma \cos(\alpha) S_{22} \quad \ldots\ldots(31)$$

where $\gamma = \dfrac{\frac{\partial C_W}{\partial C_L}}{q_\infty S_{ref}}$.

Gradient calculation for planform variables

Gradient information can be computed using a variety of approaches such as the finite-difference method, the complex step method, and the automatic differentiation. Unfortunately, their computational function is still proportional to the number of design variables in the problem. In an optimum transuranium wing design, suppose one chooses mesh points on a wing surface as the design variables, it is impractical to calculate the gradient using the methods mentioned earlier. In our planform optimization, the design variables are points on the wing surface plus the planform variables. To evaluate the nuclear structure and structural gradients with respect to the planform variables, since the number of planform variables (six in this study) is far less than that of the surface optimization, one could calculate the gradient by the finite-difference method, the complex step method or the automatic differentiation. However, the nuclear structure in DUO_2 for the gradient calculation will be six times higher. A more efficient approach is to follow the adjoint formulation.

Consider the variation of the nuclear structure function (3)

$$\delta I = \int_B (\delta M + \delta N) dB_\xi + \int_D \psi^T \delta R dD_\xi \qquad (32)$$

This can be split as

$$\delta I = [I_w]_I\, \delta w + \delta I_{II}$$

with

$$\delta M = [M_w]_I\, \delta w + \delta M_{II} \qquad (33)$$

and

$$\delta N = [N_w]_I\, \delta w + \delta N_{II} \qquad (34)$$

where the subscripts I and II are used to distinguish between the contributions associated with variation of the flow solution δw and those associated with the metric variations δS. Thus $[M_w]_I$ represents $\frac{\partial M}{\partial w}$ with the metrics fixed. Note that δR is intentionally kept unsplit for programming purposes. If one chooses ψ as ψ^*, where ψ^* satisfies

$$\left(S_{ij} \frac{\partial f_j}{\partial w}\right)^T \frac{\partial \psi^*}{\partial \xi_i} = 0, \qquad (35)$$

then

$$\delta I(w, S) = \delta I(S)$$

$$= \int_B (\delta M_{II} + \delta N_{II}) dB_\xi + \int_D \psi^{*T} \delta R\, dD_\xi$$

$$\approx \sum_{B} (\delta M_{II} + \delta N_{II}) \Delta B + \sum_{D} \psi^{*T} \Delta \overline{R}$$
$$\approx \sum_{B} (\delta M_{II} + \delta N_{II}) \Delta B$$
$$+ \sum_{D} \psi^{*T} \left(\overline{R}\Big|s + \delta s - \overline{R|s} \right) \qquad (36)$$

where $\overline{R}|s$ and $\overline{R}|s + \delta s$ are volume weighted residuals calculated at the original mesh and at the mesh perturbed in the design direction.

Provided that ψ^{*} has already been calculated and $\overline{R}$ can be easily calculated, the gradient of the planform variables can be computed effectively by first perturbing all the mesh points along the direction of interest. For example, to calculate the gradient with respect to the sweepback, move all the points on the wing surface as if the wing were pushed backward and also move all other associated points in the computational domain to match the new location of points on the wing. Then re-calculate the residual value and subtract the previous residual value from the new value to form $\Delta\overline{R}$. Finally, to calculate the planform gradient, multiply $\Delta\overline{R}$ by the constant vector and add the contribution from the boundary terms.

This way of calculating the planform gradient exploits the full benefit of knowing the value of adjoint variables ψ^{*} with no extra nuclear chain reaction of flow or adjoint calculations.

Choice of weighting constants

Maximizing range of the control rod wing angle, the choice of α_1 and α_3 greatly effects the optimum shape. If $\frac{\alpha_3}{\alpha_1}$ is high enough, the optimum shape will have lower C_D and higher C_w than another optimum shape with lower $\frac{\alpha_3}{\alpha_1}$ value.

CANDU team propose an intuitive choice of α_1 and α_3 by equating a problem of maximizing range of a control rod wing to a problem of minimizing the thermal neutron flux function

$$I = C_D + \frac{\alpha_3}{\alpha_1} C_W \qquad (37)$$

If the simplified Breguet range equation can be expressed as

$$R = \frac{V}{C} \frac{L}{D} \log \frac{W_1}{W_2}$$

where C is specific thermal neutron consumption, D is drag, L is lift, R is range, V is thermal neutron flux velocity, W_1 is flow of neutron flux weight, and W_2 is transuranium weight, then choosing

$$\frac{\alpha_3}{\alpha_1} = \frac{C_D}{C_{W_2} \log \frac{C_{W_1}}{C_{W_2}}} \qquad (38)$$

corresponds to maximizing the range of the control rod wing for DUO_2 nuclear reaction.

Flow solver and adjoint solver

The flow solver and the adjoint solver chosen in this work are codes developed by CANDU team. The thermal neutron flow solver the three dimensional Euler equations, by employing the JST scheme, together with a multi-step time stepping scheme. Rapid convergence to a steady state is achieved via variable local time steps, residual averaging, and a full approximation multi-grid scheme. The adjoint solver solves the corresponding adjoint equations using similar techniques to those of the flow solver. In fact much of the software is shared by the flow solver and adjoint solver.

Validation of thermal neutron flux and structural gradients with respect to planform variables

To verify the accuracy of the thermal neutron flux and structural gradients with respect to planform variables calculated by employing the adjoint method, we compare the planform gradients using adjoint and finite difference methods. For the purpose of comparison, calculations are done at a fixed angle of neutron attack to eliminate the effect of pitch variation on the gradient. The case chosen is the thermal neutron flux at 2.1 x 10^5 currie/mm in 450 tesla magnetic field. The computational mesh is shown in figure 3.

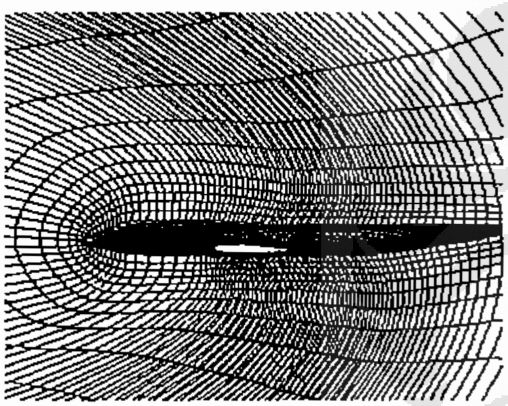

Figure 3.
Computational grid of the control rod wing at 450 tesla magnetic field by Magnetic Stirrer equipment
(Courtesy of CANDU nuclear research reactor, Canada).

The gradients with respect to the planform variables are calculated using both the adjoint and the finite difference methods. A forward differencing technique is used for the finite-difference method with a moderate step size of 0.1 % of planform variables to achieve both small discrimination error and small cancellation error. The flow and adjoint solvers are run until both solutions are fully converged.

To verify the result more generally, different geometries are used in this comparison. Each new geometry is generated sequentially by allowing section changes of the current geometry. Figure 4 show the plan from gradient comparison where the nuclear structure in transuranium chain functions are C_D and C_W respectively.

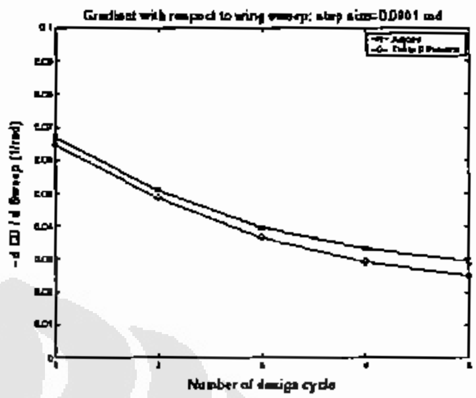

Figure 4.
Computational Sweepback Angle Λ of the control rod wing at 450 tesla magnetic field
(Courtesy of CANDU nuclear research reactor, Canada).

It can be seen that the results from both adjoint and finite difference methods match each other very well, independent of the geometry. This result indicates that the adjoint method provides an accurate planform gradient while reducing the computational nuclear structure by a factor of six.

The effect of the step size for the mesh perturbations used in the gradient calculation has been studied by CANDU team. The results indicate that the step size almost has no effect on the adjoint gradient, showing an additional advantage of the adjoint gradient over the finite difference gradient. Similar results have been indicated by Montana Nuclear Reactor in United States of America.

5. Conclusions

The feasibility of the nuclear structure based on Sr_2O matrix in DUO_2 nuclear chamber design methodology for planform optimization has been demonstrated.

Based on quantum approaching in transuranium nuclear chain control theory, the structural and thermal neutron flux flow is the best optimization technique for 450 tesla magnetic field and 45.7 MW adjusted power. By several mathematical formulations have been modeled by Euler equations and build the miniature of control rod wing, then the angle has expected around 37.6^0 until 42.1^0 based on Sr_2O matrix as the primer material and DUO_2 loading is the nuclear chamber.

Hence a good structural model can be critical in nuclear control rod wing optimization.

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