Research on associated motion simulation method and platform of control rod driving mechanism

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Abstract
The motion simulation analysis of the control rod drive mechanism is a typical multi-disciplinary cross-coupling problem covering electromagnetic field, flow field, and dynamic field. Ensuring effective simulation accuracy is an important advance for accurately predicting the reliability of nuclear reactors. In this paper, a multi-disciplinary co-simulation method is proposed based on time unit differentiation, which solves the coupling problem of parameters by micro-element thought. It can avoid affecting the accuracy of simulation results due to the inequality of multi-disciplinary parameters in the co-simulation process. This paper takes the nuclear reactor control rod drive mechanism as the verification object. The multi-disciplinary co-simulation platform in Isight is built based on the co-simulation method. By differentiating the overall process of multidisciplinary co-simulation according to time unit and using the same simulation time interval for each discipline, the Newmark method is used to determine the minimum simulation time integration step of each discipline. The multi-field co-simulation is carried out including electromagnetic field, flow field, gravitational field, and motion field of the driving mechanism in the working process. Through comparison with the actual measurement results, the simulation results have an error within 5%, which is better than existing motion simulation results of driving mechanism.

Keywords
Multi-disciplinary simulation, co-simulation, driving mechanism, micro-element thought, Newmark, Isight platform

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Introduction
With the increase of the scale of modern engineering system, the system covers more disciplines, the coupling relationship between different disciplines become more complex, and the demand of multi-disciplinary associated simulation and multi-objective optimization become more prominent. Since the 21st century, with the exploitation of non-renewable energy becoming less, nuclear energy as a new type of energy has received extensive attention from community. Due to the characteristics of strong radiation and high energy density of nuclear energy, it is an important research topic to use and control nuclear energy reasonably. The stepping magnetic lifting control rod drive mechanism is a key component of the third-generation nuclear reactor. It is energized by the coil according to given timing. The coil sequentially controls the lifting
armature, moving armature, holding armature to complete the stepping lifting, and inserting actions of the control rod to control working status of nuclear reactor. The motion process of the driving mechanism is a typical multi-field coupling complex system such as electromagnetic field, flow field, and temperature field in the liquid environment of high temperature and high pressure. The motion displacement and velocity of driving mechanism change with the dynamic variation of electromagnetic force, friction force, and liquid resistance, and its motion process is a complex multi-field coupling problem. How to ensure the simulation accuracy of the driving mechanism plays an important role in accurately predicting the reliability and life of the reactor.

Solving the motion process of driving mechanism is a transient dynamic analysis problem. For this kind of problem, the Newmark method in stepwise integration method is representative in numerical method. Taherifar et al. and Gorini and Callisto applied this method to architecture to explore how to enhance the bearing capacity of building materials and the key factors that affect the dissipation performance of equipment. Zhuogen and Pu combined the Newmark method with modal damping or approximate modal damping, and established the iterative solution process of implicit method, which can be used to calculate the dynamic response of structures with strong modal characteristics. Lu et al. employed the Newmark method to resolve differential equations and obtain the additional acceleration, then used it to perform dynamic reliability analysis of a filtering reducer. In addition, Newmark method is also widely used in geology and vibration.

The driving mechanism of nuclear reactor control rod is affected by coupling electromagnetic force and water resistance in the process of motion. At present, most of the studies are completed under a single action. For example, in the field of electromagnetic field simulation, the researchers obtained the electromagnetic characteristics of the driving mechanism and other systems in the process of transient action under different working conditions. In the aspect of flow field, Xie et al. and Xiaochen et al. carried out grid division and flow field analysis of cooling channel. Jintao et al. proposed a coupling simulation method of reactor control rod falling rod behavior based on dynamic grid, and achieved a good compromise between calculation time and solution accuracy. Some scholars have studied the motion of the driving mechanism, solved the internal calculation program of the falling rod dynamics problem, and developed a three-dimensional virtual motion system.

Based on the above methods and results of single-disciplinary analysis, the multi-disciplinary associated simulation is used to restore the real motion of the driving mechanism, and the coupling relationship between the parameters of each subject is solved. Liu et al. and Yantao and Hongbiao calculated the dynamic equation of step motion by numerical method, and establish dynamic calculation model to verify it with the help of finite element analysis tool. Luo et al. proposed a new method of co-simulation of parallel robot based on multi-platform to improve the accuracy of the dynamic response analysis of the part. Qiang et al. built a dynamic analysis system through Matlab/Simulink coupling to establish an interface, and obtain the relationship between the key motion parameters and time. Wei et al. calculated the electromagnetic field and flow field iteratively, and introduced the convergent results into the sports field to calculate. In addition to the dynamic characteristic curve, the step jump load was quantitatively analyzed for the calculation of strength and fatigue life.

At present, when carrying out multi-disciplinary associated simulation, one subject simulation model is generally selected as the center, and the design parameters of other disciplines are called through the simulation interface to complete the multi-disciplinary simulation task. Although this associated simulation method can realize the process of parameter transfer between disciplines and improve the simulation efficiency to a certain extent, there are the following two outstanding problems: one is the unequal status of design parameters in each subject, which leads to the emphasis on the design parameters of a certain discipline. In the process of multi-disciplinary associated simulation, there is no difference in status between different disciplines and different types of parameters in essence. The simulation process centered on the design parameters of a certain discipline can easily lead to the consistency constraint when solving the coupling relationship between the design parameters of a discipline or a few disciplines. The results of multi-disciplinary associated decoupling under this constraint are often different from those obtained in engineering practice. On the other hand, the number of design parameters is inconsistent. There is coupling relationship between design parameters of different disciplines in the process of associated simulation, especially that the same design parameters need to be calculated with different dimensions in different disciplines. So it is difficult to realize the real-time unification of parameters in the simulation process, which takes the simulation results of one discipline as a whole and introduces them into other disciplines as a whole. The reliability of the simulation results will be affected.

In order to solve the above two problems, in this paper, a multidisciplinary co-simulation method is proposed based on time unit differentiation. It uses Newmark method to determine the integral step size of
simulation time and bring the simulation process of each subject into the unified simulation process. The method is applied to the simulation process of control rod drive mechanism, and a multi-disciplinary associated simulation platform system is constructed. Through comparison with the actual measurement results, the simulation results have an error within 5%, which is better than the existing motion simulation results of driving mechanism.

Multi-disciplinary associated simulation method of mechanism motion based on Newmark method

According to interdisciplinary issues, the multidisciplinary co-simulation process which is based on analysis of various disciplines and their coupling constructs mapping relationships and simulation platform for model interconnection and data exchange. So it can simulate the real situation to the greatest extent and draw corresponding conclusions. For the problem that the parameter status is not equal and the dimension is not consistent in the process of multi-disciplinary associated simulation, the fundamental reason is that the coupling of parameters between disciplines is strong. In the traditional multi-disciplinary simulation method, the simulation process between disciplines is relatively independent, so it is impossible to simulate the motion of the system covering multiple disciplines. In order to improve the accuracy of multi-disciplinary associated simulation, it is necessary to ensure that the parameters of each subject can transfer and interact in real time in the simulation process. It is an effective way to solve this problem by using microelement method to differential the simulation time unit.

Multi-disciplinary associated simulation method of mechanism motion based on microelement thought

The multi-disciplinary associated simulation method based on microelement idea is shown in Figure 1. In the first, Tasks of the simulation problem need be distinguished. The mapping relationship between the subject model and the parameters of each subject involved in the associated simulation need be determined. Then the independent simulation models and the data interaction interface module between these models is developed according to the need of different disciplines. Each subject simulation model is called to calculate the associated simulation system in the micro-element unit in turn. Data transfer is carried out according to the parameter mapping relationship between each subject. The simulation result of each micro-element time period is used as part of the final result and the input part of other micro-element time periods.

Through the micro-element thought in this multi-disciplinary associated simulation method, the relationship of the complex coupling variables is solved by time unit and parameters transfer. The consistency constraint of discipline simulation center or multi-disciplinary decoupling cannot be set, which can effectively avoid the unequal status of multi-disciplinary simulation design parameters. Because this method can realize the continuous process automatically, the efficiency of the simulation process is improved. And the continuous input of parameters can be realized in multi-disciplinary co-simulation platform, which creates the favorable conditions for the optimization.

The method based on time unit differentiation can adapt to various complex motion processes. The simulation method transforms the complex multi-discipline and multi-parameter coupling problem into a simple
motion problem in micro-element time period. The time step is adjusted to ensure that the assumption of the motion simplification is true, thereby improving the simulation accuracy of the entire complex multi-disciplinary co-simulation result. Therefore, this method has strong adaptability for solving this kind of problem.

**Multi-disciplinary associated simulation model of mechanism motion based on Newmark method**

The motion process of control rod driving mechanism is a complex multi-disciplinary problem. Under the action of electromagnetic force, spring force and fluid resistance, it is necessary to solve the relationship between electromagnetic force and time and the variation law of displacement, velocity, and acceleration of driving mechanism. In order to explore this law, it is necessary to calculate the motion response of the driving mechanism under the action of external force at each time. It is difficult to find the general solution of the combination of motion equations in various disciplines because of the complexity of the coupling relationship between the external forces. The motion process can be subdivided according to time by the idea of micro-element to be simplified. According to the Kinematic equation:

\[
[M] \dddot{U}(t) + [C] \ddot{U}(t) + [K] U(t) = \{F(t)\} \tag{1}
\]

In equation (1), \([M]\), \([C]\), and \([K]\) are the mass matrix, damping matrix, and stiffness matrix of the moving mechanism. \(\{\dddot{U}(t)\}, \{\ddot{U}(t)\}, \{U(t)\}, \{F(t)\}\) are the acceleration, velocity, displacement, and external load vector of the drive mechanism at \(t\) time. The solving methods of equation (1) are mainly divided into two categories, one is the stepwise integration method. The differential equation of equation (1) is transformed into an algebra equation, and then solved by the method of algebra operation. It is necessary to introduce a reasonable relationship between displacement, velocity, and acceleration in a step interval. The equation represented by three unknown increments contains only one unknown increment, so that it can be solved by algebra equation. The other is the modal superposition method that is the method of extracting the inherent characteristic parameters of the structure. These parameters themselves are independent of the external excitation, but reveal the dynamic characteristics of the system itself and the trend of structural response under the action of external forces.

The Newmark method in the stepwise integration method makes use of the microelement idea to carry out Taylor expansion and approximate calculation of equation (1). It uses the recurrence method to concatenate each microelement section to obtain the numerical solution of the whole dynamic equation. In this paper, the motion response of the next stage of the system is deduced by the way of time integral step based on Newmark method. It is assumed that the relevant parameters at \([t, t + \Delta t]\) satisfy\(^\text{32}\):

\[
\begin{align*}
(b_4[M] + b_3[C] + [K])\{U(t + \Delta t)\} \\
= \{F(t + \Delta t)\} + [M] \left( b_1 U(t) + b_2 U(t) + U(t) \right) \\
+ [C] (b_4 U(t) + b_5 U(t) + b_6 U(t))
\end{align*}
\]

\[
U(t + \Delta t) = b_1 [U(t + \Delta t) - U(t)] - b_2 U(t) - b_3 \ddot{U}(t) \tag{2}
\]

\[
U(t + \Delta t) = b_4 [U(t + \Delta t) - U(t)] - b_5 U(t) - b_6 \ddot{U}(t) \tag{3}
\]

\[
b_1 = \frac{1}{\beta(\Delta t)^2}, b_2 = \frac{1}{\beta \Delta t}, b_3 = \frac{1}{2\beta} - 1
\]

\[
b_4 = \frac{\gamma}{\beta \Delta t}, b_5 = \frac{\gamma}{\beta} - 1, b_6 = (\frac{\gamma}{2\beta} - 1)\Delta t
\]

Where: \(\beta\) is the coefficient of \(\Delta t^2 \dddot{U}(t)\) obtained by Taylor expansion and truncation of \(U(t + \Delta t)\); \(\gamma\) is the coefficient of \(\Delta t^2 U(t)\) obtained by Taylor expansion and truncation of \(U(t + \Delta t)\).

The above equation shows that after the inherent parameters of the system \([M], [C], [K],\) the variation of the external load with time \(\{F(t)\}\) and the initial parameters of the system motion \(\{U(0)\}\) are known, the motion time can be microelement by setting the time step \(\Delta t\), and then the whole process of the motion can be solved by recursion. Among them, \([M], [C], [K],\) and \(\{F(t)\}\) use each model analysis software for simulation. Because the Newmark method need not distinguish whether the system has proportional damping or not, it can be extended to solve the nonlinear system according to the recurrence process in the time domain so that achieve unconditional stability under certain conditions and high accuracy at a reasonable value of \(\Delta t\).\(^\text{33}\)

**Determination and accuracy analysis of microelement time step**

The selection of \(\Delta t\) in the process of multi-disciplinary associated simulation based on microelement method will have a great impact on the accuracy of the simulation results. For the motion process of the control rod drive mechanism, the acceleration changes because of the continuous change of the external load. The time step must be as small as possible in order to make the
armature closer to the real situation in the process of motion, so that the accuracy of the simulation results become higher. But in the actual calculation and simulation process, the time step is a set value which can’t tend to infinitesimal. The decrease of time step will increase the number of recursion steps so that the calculation efficiency is affected. The multi-disciplinary associated simulation based on micro-element method must consider the relative balance between the simulation accuracy, that is, the time step and the amount of computation. Under different engineering problems and working conditions, the values are often quite different. In order to reduce the amount of calculation in the process of determination, the approximate range should be given first, and then the fine search should be carried out in this range. With the zero approaching, the difference between the values of different groups of simulation results gradually is decreased and a relatively stable state is reached. Considering the amount of computation, the \( \Delta t \) which makes simulation results tend to be relatively stable in the process of reduction in the process of actual simulation, can be used as the time step of multi-disciplinary associated simulation. In this paper, in order to determine the time step of simulation of different engineering problems, the calculation method of \( \Delta t \) is proposed as follows:

**Condition 1.** Assuming that the total time length of the simulation process under the engineering problem is \( T \), the value is calculated by dichotomy, and the approximate range is determined \( \Delta t \).

\[
R^2 = 1 - \frac{\sum_{i=1}^{n} (y_i - \bar{y})^2}{\sum_{i=1}^{n} (y_i - \bar{y})^2}
\]  

(6)

In equation (6), \( R^2 \) is the correlation index, which is used to indicate the fit of the regression equation; \( y_i \) is the longitudinal coordinate value corresponding to the first curve; \( \bar{y} \) is the average value of the longitudinal coordinates of the first curve; \( \bar{y}_i \) is the longitudinal coordinate value corresponding to the second curve. Then follow the steps:

**Step1:** Input: \( \Delta t_1 = \frac{T}{2}, \Delta t_2 = \frac{T}{4}, \Delta t_3 = \frac{T}{8} \).

**Step2:** Calculate the simulation results when \( \Delta t_1, \Delta t_2, \Delta t_3 \) and fit the curve \( I_1, I_2, I_3 \).

**Step3:** Calculate the correlation index \( R^2_1, R^2_2 \) according to equation (6).

\[
R^2_1 = 1 - \frac{\sum_{i=1}^{n} (y_{1i} - \bar{y}_1)^2}{\sum_{i=1}^{n} (y_{1i} - \bar{y}_1)^2}, \quad R^2_2 = 1 - \frac{\sum_{i=1}^{n} (y_{2i} - \bar{y}_2)^2}{\sum_{i=1}^{n} (y_{2i} - \bar{y}_2)^2}
\]

**Step4:** Calculate \( C_1 = \frac{R^2_1}{R^2_2} \).

**Step5:** When \( C_1 \notin \left[ \frac{1}{2}, 2 \right], \Delta t \in \left[ 0, \frac{T}{8} \right] \);

When \( C_1 \notin \left[ \frac{1}{2}, 2 \right], \) go step 6.

**Step6:** Input \( \Delta t_4 = \frac{T}{16} \).

**Step7:** Calculate the simulation results when \( \Delta t_4 \) and fit the curve \( I_4 \).

**Step8:** Calculate \( R^2_3 \) of \( I_3, I_4 \).

**Step9:** Calculate \( C_2 = \frac{R^2_3}{R^2_2} \).

**Step10:** When \( C_2 \in \left[ \frac{1}{2}, 2 \right], \Delta t \in \left[ 0, \frac{T}{16} \right] \).

**Step11:** Repeat until \( C_n \in \left[ \frac{1}{2}, 2 \right], \Delta t \in \left[ 0, \frac{T}{2^n + 2} \right] \).

**Condition 2:** Assuming that the approximate range of \( \Delta t \) is \( \left[ 0, \frac{T}{2^n + 2} \right] \) which determined in condition 1. Use the buried point method to determine the exact value of \( \Delta t \). Follow the steps:

**Step1:** Input: \( \Delta T_{11} = \frac{T}{2^n + 4}, \Delta T_{12} = \frac{3T}{2^n + 2}, \Delta T_{13} = 3T, \Delta T_{14} = \frac{T}{2^n + 2} \).

**Step2:** Calculate the simulation results when \( \Delta T_{11}, \Delta T_{12}, \Delta T_{13}, \Delta T_{14} \) and fit the curve \( l_{11}, l_{12}, l_{13}, l_{14} \).

**Step3:** Take 10 points on each curve and ensure that their abscissas correspond to the same, set point \( a_{10} \sim a_{19} \) on \( l_{11} \), point \( a_{20} \sim a_{29} \) on \( l_{12} \), and so on.

**Step4:** Set \( \sigma_n = \sum_{i=1}^{n} \frac{a_{i} - \bar{a}}{C_n} \), \( n = 1, 2, \ldots, 10 \).

**Step5:** Calculate standard deviation \( \sigma_n = \sqrt{\frac{\sum_{i=1}^{n} (a_i - \bar{a})^2}{n}} \).

**Step6:** Calculate \( \sigma = \sum_{i=1}^{10} \sigma_i \).

**Step7:** When \( \sigma \leq \varepsilon \) (\( \varepsilon \) is determined according to the actual engineering accuracy requirements), make \( \Delta t = \Delta T_2 = \frac{T}{2^n + 2} \).

When \( \sigma > \varepsilon \), buried point in \( [0, \Delta T_2] \), repeat until find \( \sigma, \Delta t \) which satisfy value.

Before the simulation of the engineering problem, the value range of \( \Delta t \) can also be roughly determined by consulting relevant documents to reducing the amount of calculation, instead of condition 1 for the initial range determination process.

**Multi-disciplinary associated simulation method of control rod drive mechanism based on Newmark**

A numerical method for solving the motion of fuel bar drive mechanism based on Newmark method

The control rod drive mechanism of reactor is affected by electromagnetic force, water resistance, spring force
in the process of motion. The external load changes constantly with the movement process of the driving mechanism, and there is a coupling relationship between them. In order to simulate and analyze this kind of complex motion process under the chance of these load, the motion process of driving mechanism is subdivided according to time based on Newmark method. The multi-disciplinary simulation and parameter transfer are carried out in the micro-element unit after microelement. The motion parameters of the driving mechanism are obtained by recurrence of the simulation results after microelement.

The motion of the armature part of the driving mechanism is analyzed according to the actual size and material parameters. The mass matrix [M], stiffness matrix [C], and damping matrix [K] are the inherent properties of the system, which do not change with the motion of the object, and can be derived by finite element analysis software. Electromagnetic force, fluid resistance, and spring force change in the process of motion, and the calculation equation takes the lifting process as an example.34,35:

Electromagnetic force:

\[
F_d(t) = \frac{\mu_0 S_1 N^2 I^2}{2(\mu_0 S_1 r + l_1 - \{U(t)\})^2} \quad (7)
\]

Spring force:

\[
F_c = k \cdot \{U(T)\} \quad (9)
\]

External load:

\[
F(t) = F_d(t) - F_f(t) - F_s(t) \quad (10)
\]

In order to study the variaion process of displacement, velocity, and acceleration of armature in the process of driving mechanism motion, the average acceleration method, a special form of Newmark method, when \( \gamma = \frac{1}{2}, \beta = \frac{1}{4}(t, t + \Delta t) \). Assuming that the acceleration is constant, it is equivalent to the ladder method to approximate the acceleration on the interval. So it has the same second-order accuracy as the ladder integral rule, and this set of values can make the method unconditionally stable.

Bring equations (7)–(10) back to equation (2):

\[
(b_1 \{M\} + b_4 \{C\} + \{K\}) \{U(t + \Delta t)\} = \frac{\mu_0 S_1 N^2 I^2}{2(\mu_0 S_1 r + l_1 - \{U(t)\})^2} - S_2 \left[ \sum \frac{0.5cp \{U(t)\}^2 QL}{S_3} + Lpa + 0.5\xi \rho v_0^2 \right] - k \cdot \{U(t)\} + \{M\} \{b_1 \{U(t)\} + b_2 \{U(t)\} + b_3 \{\bar{U}(t)\}\} + \{C\} \{b_4 \{U(t)\} + b_5 \{\bar{U}(t)\} + b_6 \{\bar{\bar{U}}(t)\}\} \quad (11)
\]

\[
b_1 = \frac{1}{\beta(\Delta t)^2} = \frac{4}{(\Delta t)^2}, \quad b_2 = \frac{1}{\beta \Delta t} = \frac{4}{\Delta t}, \quad b_3 = \frac{1}{2\beta} - 1 = 1
\]

\[
b_4 = \frac{\gamma}{\beta \Delta t} = \frac{2}{\Delta t}, \quad b_5 = \frac{\gamma}{\beta} - 1 = 1, \quad b_6 = (\frac{\gamma}{2\beta} - 1) \Delta t = 0 \quad (12)
\]

Bring equation (12) back to equations (3), (4), (11):

\[
\left( \frac{4}{(\Delta t)^2} \{M\} + \frac{2}{\Delta t} \{C\} + \{K\} \right) \{U(t + \Delta t)\} = \frac{\mu_0 S_1 N^2 I^2}{2(\mu_0 S_1 r + l_1 - \{U(t)\})^2} + \left\{ \frac{4}{(\Delta t)^2} \{M\} + \frac{2}{\Delta t} \{C\} - k \right\} \{U(t)\} - S_2 \left[ \sum \frac{0.5cp \{U(t)\}^2 QL}{S_3} + Lpa + 0.5\xi \rho v_0^2 \right] + \left( \frac{2}{\Delta t} \{M\} + \{C\} \right) \{\bar{U}(t)\} + \{M\} \{\bar{\bar{U}}(t)\}
\]

\[
\{U(t + \Delta t)\} = \frac{4}{(\Delta t)^2} \{U(t + \Delta t)\} - \{U(t)\} - \frac{4}{\Delta t} \{U(t)\} - \{\bar{\bar{U}}(t)\} \quad (14)
\]
\begin{equation}
\{U(t + \Delta t)\} = \frac{2}{\Delta t} \{U(t + \Delta t)\} - U(t) - \dot{U}(t) \quad (15)
\end{equation}

**Multi-disciplinary associated simulation process of control rod driving mechanism**

Based on the Newmark method, the numerical calculation of the multi-disciplinary associated motion of the control rod driving mechanism is solved. The equations (7)–(9) shows that the external load of the driving mechanism has a nonlinear relationship with the motion parameters in the process of its motion. The whole process of armature from initial motion to adsorption and impact is differential. The time step is \(\Delta t\). According to the average acceleration method, it is assumed that the acceleration of armature remains unchanged in \((t, t + \Delta t)\), the armature is subjected to the associated action of electromagnetic force, water resistance, and spring force in the process of upward motion. According to the calculation of the three forces in equations (7)–(9) and the coupling relationship among different parameters, the mapping relationship of coupling parameters between different disciplines in the simulation process is constructed in Figure 2.

1. The magnitude of electromagnetic force varies with the change of armature position and the current value loaded on coil by external circuit. For the electromagnetic field model of driving mechanism, the input is the coil current value (loaded according to the actual requirements) and the displacement of armature at \(t\) time (assuming the initial position of armature is 0). The electromagnetic force generated by the electrified coil of the armature moves upward for a distance, which is \(U(t)U(t + \Delta t) - U(t)\). The electromagnetic force \(F_d\) (The average value in the process) in \((t, t + \Delta t)\) is transferred to the kinematic model for dynamic analysis. The initial and final velocity moving upward under the action of electromagnetic force is transferred to the flow field model of the driving mechanism for flow field analysis.

2. It is assumed that the acceleration of reactor coolant flow is constant, and the variable factors that determine the fluid resistance of armature are the velocity of upward motion and the velocity of coolant. The velocity of coolant can be predefined in the flow field model. Thus the input of the flow field analysis model is the initial velocity \(U(t)\) and final velocity \(U(t + \Delta t)\) of armature motion in \(\Delta t\). And the resistance value \(F_f\) of armature moving (Take the average value) in \(\Delta t\) is obtained after the analysis and calculation of the flow field model. Then transmit it to the dynamic force field calculation model for motion analysis.

3. In the dynamic field model, it is necessary to carry out the movement simulation of the armature integrated the electromagnetic force, fluid resistance, spring force (all average) and gravity, velocity, and acceleration of the armature calculated at the end of \(t\) time calculated by other disciplines. The armature motion parameters \(U_{t+\Delta t}, U_{t+\Delta t}, U_{t+\Delta t}\) at the end of the moment \(t + \Delta t\) need be solved. Bring the \(U_{t+\Delta t}\) and \(U_{t+\Delta t}\) transfer to the electromagnetic field analysis model and simulated in the micro-element of \((t + \Delta t, t + 2\Delta t)\).

The simulation process of the driving mechanism mainly includes:

1. The initial point of armature motion is set to the zero point of position coordinate, the direction of motion is positive, and the initial velocity is \(U_0 = 0, \dot{U}_0 = 0\).

2. According to the parameter mapping relationship, the multi-disciplinary simulation process is built. The parameters obtained from the motion process simulation at each \(\Delta t\) are derived for the graph line fitting of the armature motion process.

3. In essence, Newmark method is a kind of recurrence process, which needs to be deduced by the idea of cycle in motion simulation of driving mechanism based on Newmark method. The most critical step in the construction of the cycle is the simulation analysis data \(U_{n\Delta t}, U_{n\Delta t}, U_{n\Delta t}\) of the dynamic field at the end of the cycle in the above parameter mapping. It is transferred to the beginning of the next cycle, that is, the motion simulation analysis of the armature in the microelement \((n\Delta t, n\Delta t + \Delta t)\). The starting point (1) of the cycle has been given, and the end point of the cycle is the completion of the movement of the armature from the beginning of adsorption to the collision with the electromagnet.

The number of cycles: \(n = \frac{T}{\Delta t}\). \(T\) is the total time of motion.

In the concrete realization of the loop, the traditional multi-disciplinary simulation process generally adopts the way of manual introduction, which carries on the parameter transfer and the model setting among the disciplines. Because the value of \(\Delta t\) must be as small
as possible to ensure the accuracy of the simulation, \( n \) is often large. The way of manually importing parameters is time-consuming and laborious. In summary, the multi-disciplinary optimization platform is used to realize the input transmission and output of parameters between different disciplines in a certain order. The cycle process and simulation analysis are completed automatically.

**Multi-disciplinary associated simulation platform for control rod drive mechanism**

Based on the proposed multi-disciplinary associated simulation method of control rod drive mechanism, this paper constructs a multi-disciplinary associated simulation platform of control rod drive mechanism based on Isight. Isight is a tool platform which can integrate multiple simulation software. It can call the integrated simulation software sequentially through the established simulation flow, and realize the mapping and interaction of simulation data by developing the interface program between the simulation model and the platform. The key to build the platform is to build the simulation model interface and data interaction mode. Because \( \Delta t \) is used to divide the simulation time when solving the mechanism motion process in Newmark method, the simulation platform need be divided according to the simulation time. It can also realize the function of process recurrence and parameter transfer. The Isight software, which can unify the simulation time of each process and realize the recurrence goal through cycle, is selected as the multi-disciplinary associated simulation platform to realize the motion simulation of driving mechanism.

**Construction of platform simulation model interface module**

In this paper, Maxwell, Fluent, and Adams are selected for the simulation and analysis tools of electromagnetic field, flow field, and dynamic field of control rod driving mechanism. Because the simulation software of different disciplines is relatively independent, secondary development is needed when constructing the model interface traditionally between multiple simulation models. Isight tool integrates each software through the unified platform, which effectively reduces the difficulty and universality of the interface construction. According to the Newmark method, the simulation process is divided into several time periods, and the interface content changes with the calculation model in each simulation. Only by finding the location of the required data in each simulation, the results of each model analysis can be accurately and timely imported into the platform, and the data transmission can be carried out according to the preset ways. The aim is to ensure the correctness and timeliness of the interface between the model and the platform. Taking electromagnetic field (Maxwell) as an example, the construction process of simulation model interface module is shown in Figure 3. Isight integration component simcode module includes input data exchange, execution of external application program, and output data exchange. The two data exchange parts are the interface between the simulation model file and the Isight platform. The input file and output file of electromagnetic field simulation model are exported to simcode. Transmission process of input and output parameters can be completed by writing and reading the corresponding position data.

The interface file for the electromagnetic field model is as follows:
The data of the corresponding position in the electromagnetic field can be set as input or output variables, such as the initial position (“InitPos:=”), the initial velocity (“Velocity:=”), the output electromagnetic force (“Force=”), etc. The interface between the analysis model and the integrated platform can be completed. In order to realize the automatic simulation process, the integrated platform must be able to automatically call the corresponding analysis software for simulation. The call command must be saved in file format of bat.

When the microelement idea is used to build the associated simulation platform of the driving mechanism, it is necessary to call the analysis software repeatedly to analyze and output the results according to the given simulation steps under different input conditions in order to realize the recurrence process. The solution to this problem is to input the simulation process into simcode as a script. Only the value of the input parameters is changed in the script at each simulation, and the rest of the simulation process is repeated. Some contents of the simulation script of electromagnetic field, flow field, and dynamic field are shown as follows:

(1) Maxwell simulation script:
```plaintext
oModule.EditSetup"Setup1",
Array(
"NAME:Setup1",
"Enabled:=".true,
"NonlinearSolverResidual:=".0.0001",
"TimeIntegrationMethod:=".0,
"StopTime:=".4ms",
"TimeStep:=".0.1ms",
"StartValue:=".0ns",
"StopValue:=".820ms",
"StepSize:=".1ms",
"UseAdaptiveTimeStep:="false,
"InitialTimeStep:=".0.002s",
)
```

(2) fluent simulation script:
```plaintext
setup1.SendCommand(Command="(cx-gui-item"Profiles*PanelButtons*PushButton4(Apply))")
```

(3) admas simulation script:
```plaintext
undo begin
marker create
marker=.MODEL_1.Xiantie_Yidong_1.MARKER_65
&adams_id=65
&location = 23.35, -637.41, -16.26
&orientation = 180.0, 90.0, 180.0
function = “10000”
if cond =
("End Time” == “Forever”)
```
After the input and output file templates in simcode are setting and the corresponding program call commands and scripts are writing, the process of building the interface between the model and the simulation platform is realized, and the data interaction setting is entered.

**Platform data interaction module construction**

When constructing a multi-disciplinary simulation platform, data must be interacted and transmitted between analysis models of various disciplines according to a certain logical relationship. The data interaction method in Isight is to define the input and output parameters of each model on the premise that the model interface is created. Then establish the corresponding mapping relationship through the connection method in the mappings interface. According to the time dimension assumption made according to the Newmark method, the input and output parameters of each model in each time of \((t, t + \Delta t)\) period are shown in Table 1.

Based on the driving mechanism motion multi-disciplinary associated simulation time microelement, associated simulation process between various disciplines are completed through the construction of a loop. The criteria for the number of cycles and the termination of cycles are defined in the “LOOP” component as 38 times \((n = \frac{T}{\Delta t}, \text{assuming a time step of 1.0 ms})\) and \(F_t > G\), \(X < 17.1\) mm (the total running length of the armature is 17.1 mm to ensure that the armature is always in the rising process). The current variable \(I\) is entered in “LOOP” as an array, and each value in the array corresponds to the input value of the current in one cycle. In order to transfer the displacement at the end of each cycle to the electromagnetic force in the next cycle, it is necessary to modify the value of the displacement variable in the input interface file of Maxwell. In the construction of simulation workflow, by adding “Data Exchange” component before Maxwell component, the output displacement \(x_2\) of Adams at the end of the last cycle is read at the beginning of each cycle. When \(x_1\) is modified, the data interaction between the two analysis models is established to realize the completion of the cycle and deduce the recurrence process. Based on the above methods and parameter mapping, the associated simulation platform of the driving mechanism built on Isight is in Figure 4.

**Table 1. Interactive content of design parameters of each simulation model.**

| Analysis model | Input parameter | Output parameter |
|----------------|-----------------|-----------------|
| Maxwell        | Displacement \(x\) (end of previous moment), velocity \(V\) (end of previous moment), current \(I\). | Electromagnetic force \(F_d\), velocity at the beginning and end of the time step \(V_1, V_2\). |
| Fluent         | Velocity at the beginning and end of the time step \(V_1, V_2\). | Resistance \(F_t\). |
| Adams          | Electromagnetic force \(F_d\), resistance \(F_t\), spring force \(F_s\), displacement \(x\) (at the end of the previous moment), velocity \(V\) (at the end of the previous moment). | Displacement \(x\), velocity \(V\), acceleration \(a\). |
existing motion simulation results of driving mechanism. The experimental results confirm that the proposed method in Section 2.3 of this paper can meet the calculation accuracy and improve the calculation efficiency, which is feasible in the application of driving mechanism.

![Figure 4. Associated Motion Simulation workflow based on Isight.](image)

**Table 2.** Points and mean calculation when \( i (i = 1 \rightarrow 4) \).

|   | \( i = 1 \) | \( i = 2 \) | \( i = 3 \) | \( i = 4 \) | \( \bar{a}_n \) | \( \sigma_n \) |
|---|---|---|---|---|---|---|
| \( a_0 \) (\( t = 0 \)) | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.000 |
| \( a_1 \) (\( t = 4 \)) | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.005 |
| \( a_2 \) (\( t = 8 \)) | 0.01 | 0.00 | 0.05 | 0.05 | 0.05 | 0.005 |
| \( a_3 \) (\( t = 12 \)) | 0.06 | 0.05 | 0.12 | 0.12 | 0.13 | 0.009 |
| \( a_4 \) (\( t = 16 \)) | 0.14 | 0.13 | 0.20 | 0.20 | 0.22 | 0.021 |
| \( a_5 \) (\( t = 20 \)) | 0.25 | 0.23 | 0.34 | 0.34 | 0.35 | 0.029 |
| \( a_6 \) (\( t = 24 \)) | 0.39 | 0.36 | 0.48 | 0.48 | 0.53 | 0.036 |
| \( a_7 \) (\( t = 28 \)) | 0.58 | 0.54 | 0.85 | 0.85 | 0.82 | 0.130 |
| \( a_8 \) (\( t = 32 \)) | 0.90 | 0.81 | 4.08 | 4.08 | 4.25 | 0.439 |
| \( a_9 \) (\( t = 38 \)) | 3.91 | 4.37 | 4.62 | 4.62 | 4.25 | 0.439 |
| \( \bar{a} \) | / | / | / | / | / | 0.067 |

**Figure 5.** \( \Delta T_{11} = 0.5 \text{ms} \).

**Figure 6.** \( \Delta T_{12} = 1.0 \text{ms} \).
Simulation process and result analysis of various disciplines when $\Delta t = 0.5ms$

**Electromagnetic.** The electromagnetic working principle of the control rod drive mechanism is that the electromagnetic field is generated by the working coil installed on the outside of the claw shell. The electromagnetic field passes through the claw shell, control the magnetic pole and armature to drive the claw action, and finally make the drive rod and control rod which is connected with it move. The input parameters of electromagnetic field include external coil current, initial displacement and initial velocity. The electromagnetic model in Maxwell is shown in Figure 9. The coil current is controlled by an external circuit to control the nuclear reactor components to complete the specified action. The output $F_d$ of the electromagnetic field when $\Delta t = 0.5ms$ is shown in Figure 10. It can be seen from the diagram that the electromagnetic force increases with the passage of time. The growth rate becomes faster. When $n = 76 (t = 38 ms)$, the armature moves to the end and attracts the magnetic pole, and the current is the maximum value. The electromagnetic force reaches the peak, which is about 46,000 N. When the lifting armature just is collided with the lifting magnetic pole, the distribution of magnetic induction intensity generated by the lifting coil is shown in Figure 11.

**Flow field.** The control rod driving mechanism is distributed inside the top cover of the reactor pressure vessel, and its surroundings are filled with high-temperature water heated after flowing through the fuel rods. When the drive mechanism moves the control rod, it is subject to fluid resistance. These fluid resistances include the end pressure resistance, the shape resistance, the viscous resistance, etc. The end pressure resistance has a greater impact on the movement process of the drive mechanism. The dynamic mesh technique is used to analyze and calculate fluid resistance. The average value of the initial and final velocities $v_1, v_2$ of the field is taken as the input velocity of the flow field. The model in Fluent is shown in Figure 12. The flow channel and direction of water in the driving mechanism are taken into account. The dynamic grid method is used to calculate the water resistance value as shown in Figure 13.

When the armature moves, it is accelerated by the electromagnetic lifting force generated by the lifting magnetic pole, and the fluid resistance during the movement reduces the acceleration increase. With the increase of speed, the resistance of the fluid continues to increase. It is noted that the final velocity $v_2$ is equal to 0 when $t = 38 ms$ due to the attraction of the electromagnet, so the value of resistance $F_f$ decreases. The speed of the lifting armature reaches the maximum at the end of the upward movement, that is, the moment before it collides with the lifting magnetic pole. At this time, the pressure difference and the fluid resistance on each surface of the lifting armature reach the maximum. The armature is simulated in the flow field at this moment, and the simulation results of pressure distribution are shown in the Figure 14.

**Motion simulation.** During the upward movement of the moving armature, the power is the electromagnetic force generated by the moving coil, and the resistance includes its own gravity, spring force, and fluid resistance. In the initial stage of upward movement, the electromagnetic lifting force of the moving armature is
not enough to overcome the resistance, and the moving armature remains stationary. As the value of current increase and reach stability, the electromagnetic lifting force exceeds the resistance, and the armature starts to move upward. As the moving armature moves up, the electromagnetic lifting force is further increased. It causes the speed and acceleration to rise continuously, and the fluid resistance it receives also increases. When it moves to the top, the armature collides with the magnetic pole and attracts.

When establishing the analysis model in Adams as Figure 15, it is necessary to set the stiffness coefficient and initial length of the spring. The displacement $x$, velocity $v$, and acceleration $a$ calculated by Adams are taken as the output of the results of the whole multi-disciplinary associated simulation. The motion curve of the control rod drive mechanism with time $x - n, v - n, a - n$ is obtained as shown in Figures 16 to 18, where $n$ is the number of cycles.

It can be seen from the diagram that with the increase of the displacement of the driving mechanism, the distance between the armature and the magnetic pole of the driving mechanism is gradually shortened, and velocity and acceleration are increased. In 0–30 ms, the velocity of motion rises slowly. From 30 ms, the acceleration increases gradually until the armature collides with the magnetic pole. The velocity of collision is about $3800 \text{mm/s}$, and the acceleration is about $1.8 \times 10^6 \text{mm/s}^2$, in accordance with the actual situation.
Conclusion

In this paper, a multi-disciplinary associated simulation method which uses time unit differentiation is proposed based on microelement idea and Newmark method, in order to solve the problem that the multi-disciplinary parameters are not equal and dimensional inconsistency caused by the traditional multi-disciplinary simulation. It makes parameters be transferred between various disciplines in each micro-element unit to solve the complex coupling relationship. The determination steps and principles of time integral step size are established from the point of view of improving the simulation accuracy.

With this method as a theoretical guide, Isight software is used as a tool to illustrate the process of building a multi-disciplinary co-simulation platform for the target in the paper. The process includes unifying the simulation time of each process, building simulation models and platform interfaces of various disciplines, and establishing the mapping between parameters according to the coupling relationship. As a whole, the recursive process is deduced in a cyclic manner to realize the joint simulation process of complex multidisciplinary problems.

The control rod drive mechanism is taken as the analysis object. A multidisciplinary joint simulation model is established through the Isight platform including electromagnetic field, flow field, and sports field. Under the given accuracy requirement, the time step $t = 0.5 \text{ms}$ is determined. The motion parameter curve of the driving mechanism under certain working conditions is obtained. The error between the result and the measured value is small, which confirms the feasibility and efficiency of this method in solving such problems.

When using the multi-disciplinary co-simulation method proposed in this paper to solve the motion problem of the driving mechanism, the change of input parameters and the differential time unit will have an uncertain impact on the calculation result. The paper has carried out an analysis of the impact that the change of each micro-element time unit. The uncertainty analysis of the calculation results of other parameters will be described in detail in the subsequent work.
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Figure 15. Three-dimensional model diagram of motion field analysis.

Figure 16. $x - n$ curve.

Figure 17. $v - n$ curve.

Figure 18. $a - n$ curve.
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