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Full Simulation of AC Contactor in the Dynamic Process Based on Finite Element Method

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Abstract. *3D dynamic full simulation model of AC contactor applied in air-condition which consists of contact and electromagnetic system is built in this paper. The model considers effects caused by friction force and material deformation during the collision. 3D motion mathematical models which include constitutive equations of material, motion equation and boundary constraint is built. The model is verified through experiment. The whole dynamic process of AC contactor can be calculated by using the 3D model, especially for the bounce of contacts and cores. It lays the theoretical foundation for improving the whole performance of AC contactor. Moreover, it also provides the theory basis for the control of AC contactor in the closing process.*

Keywords:ANSYS/LS-DYNA; Contactor; Full simulation; Dynamic process.

1. **Introduction.** Contactor is widely used for switching AC and DC circuit frequently. The bounce will happen due to the impact between moving and static contacts. It will affect the system performance. Moreover, the arc ablation caused by contact bounce will reduce the electrical endurance of contactor. Especially when AC contactor is applied in AC3 and AC4 categories, which closing current is 6 times of rated current. Therefore, the contact bounce becomes one of the main reasons which affect the electrical endurance of AC contactor. The reduction of contact bounce is critical step to increase the electrical endurance of AC contactor. Recently, with the rapid development of computer technology, CAE(computer aided engineering) as been widely applied in the design and research of electric appliance. ANSYS, ADMAS, ANSOFT are the typical representations.

AC contactor can be divided into three parts: electromagnetic mechanism, contact system and the linkage part. Most of the researchers are focused on arc and electric contact in the contact system. Characteristics calculation, simulation and optimization design are mainly applied in electromagnetic mechanism [1]-[7].However,combined simulation of contact system and electromagnetic mechanism has been initiated in recent years [8]-[13].There is still a lot of work should be done.

Virtual design technology has been brought in this paper. The 3D dynamic full simulation model of AC contactor proposed considers the friction between every contact faces and solves the problem of deformation in the collision process of contacts and cores. The whole moving and bounce process of contacts and cores can be calculated through the model. The model will not only analyze current, flux linkage, average velocity and displacement, but also the displacement and velocity curves of any part and point. It lays the theoretical foundations for improving the whole performance index of AC contactor. It also gives the guidance to virtual design for low-voltage apparatus.

2. Mathematical models of 3D dynamic full simulation of AC contactor.

2.1. Mechanical model of AC contactor. 3D mechanical model of AC contactor applied in air-condition is shown in Fig.1. The electromagnetic mechanism consists of moving core, static core, shading coil, core spring. The contact system consists of moving contact, static contact and contact spring.These two parts of contactor are connected through plastic bracket. When the coil is switched on, the moving core will drive the contact to move through plastic bracket when the magnetic force is greater than the initial compression force of core spring until the contacts impact and the bounce of contacts happens. And then, the moving core will move on until the collide of cores. The bounce caused by contacts is called once contact bounce, and the twice contact bounce is caused by the bounce of cores. As the analysis above, the dynamic process mainly depend on the mechanical motion process of contact and core,such as their velocity, displacement, bounce and so on. Because of the strong coupling between the force field and electromagnetic filed, there are difficulties for making sure of the computational accuracy in the whole dynamic process.

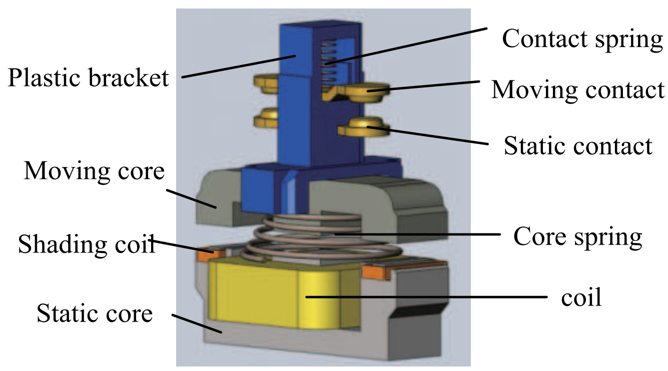


FIGURE 1. Mechanical model of AC contractor

2.2. Mathematical model of AC contactor in the closing process. The moving parts will contact and impact in the whole closing process. Especially for the cores and contacts, the impact velocity is much faster than the other impact surfaces. It will result in deformation which will affect the calculation result and it should be brought in the mathematical model. Therefore, bounce of contactor in the closing process must be restricted by constitutive equation of material, motion equations and boundary conditions.

1.Constitutive equation: used to describe the deformation characteristic when collision happens and decided by material characteristic. The equation can be expressed by generalized Hooke's law:

$$\mathbf{S}_{ij} = \mathbf{C}_{ijkl} \cdot \boldsymbol{\varepsilon}_{kl} \tag{1}$$

where $\mathbf{S}_{ij}$ is stress component, $\mathbf{C}_{ijkl}$ is material constant, $\boldsymbol{\varepsilon}_{kl}$ is strain rate.

2. Motion equations: used to describe the change of motion parameters in the closing process, including bounce. They must obeys the law of mass conservation, momentum conservation and energy conservation. The Cauchy stress equation is applied in to calculate the displacement after deformation during the collision. As the collision process is only within millisecond to complete, heating consumption of cores and contacts in the collision process can be ignored and just considering the consumption of kinetic energy in

the form of internal energy. The control functions of movable parts in the closing process can be written as:

Momentum conservation equation:

$$\boldsymbol{\sigma}_{ij,j} + \rho \mathbf{f}_i = \rho \ddot{\mathbf{x}}_i \tag{2}$$

where $\boldsymbol{\sigma}_{ij,j}$ is cauchy stress per unit mass of movable parts, ρ is density of movable parts, $\mathbf{f}_i$ is body force per unit mass of movable parts, $\ddot{\mathbf{x}}$ is acceleration per unit mass of movable parts. Mass conservation equation:

$$\rho V' = \rho_0 \tag{3}$$

where ρ_0 idunit initial mass density when deformation happen,$\rho V'$ is relative volume of deformable objects before and after deformation. Energy equation:

$$\dot{\mathbf{E}} = V\mathbf{S}_{ij}\dot{\boldsymbol{\varepsilon}}_{ij} - (\mathbf{p} + \mathbf{q})V' \tag{4}$$

where $\dot{\mathbf{E}}$ is differential of energy to time for movable parts, V is volume of current movable parts, $\mathbf{S}_{ij}$ is deviator stress, $\dot{\varepsilon}_{ij}$ is strain rate tensor of movable parts when contact happens, $\mathbf{p}$ is pressure, $\mathbf{q}$ is viscous resistance of volume.And $\mathbf{S}_{ij} = -\sigma_{ij} + (\mathbf{p} + \mathbf{q})\delta_{ij}$, where δ_{ij} - the Kronecker function; $\mathbf{p} = -\sigma_{ij}/3 - \mathbf{q}$.

They are three partial differential equations as showed above. They can be solved together with the relationship of strain and displacement of cores and contacts in the closing process and the materials. There is only one solution in the setting boundary. Cralerkin method is applied in to determine the unit characteristics and the equations can be solved through finite element method. The weak form of equilibrium equations of Cralerkin method can be showed as:

$$\int_V (\rho \ddot{\mathbf{x}}_i - \boldsymbol{\sigma}_{ij,j} - \rho \mathbf{f}_i)\delta \mathbf{x}_i dV + \int_{S^3} (\boldsymbol{\sigma}_{ij}^+ - \boldsymbol{\sigma}_{ij}^-)\mathbf{n}_j \delta \mathbf{x}_i dS + \int_S^1 (\boldsymbol{\sigma}_{ij}\mathbf{n}_j - \mathbf{t}_i)\delta \mathbf{x}_i dS = 0 \tag{5}$$

where $\mathbf{t}_i$ id force load of surface, $\mathbf{n}_j$ is outward normal cosine of surfaces out of the movable parts. Divergence theorem and stepping integration are used in (5) and then the variation equation based on principle of virtual work can be got as following:

$$\int_V (\sigma_{ij}\delta \mathbf{x}_i)_{,j} dV = \int_{S^1} \boldsymbol{\sigma}_{ij}\mathbf{n}_j \delta \mathbf{x}_i dS + \int_{S^3} (\boldsymbol{\sigma}_{ij}^+ - \boldsymbol{\sigma}_{ij}^-)\mathbf{n}_j \delta \mathbf{x}_i dS \tag{6}$$

The movable parts including moving cores, contacts and so on. These parts can be discretized into finite element. And then, the total potential variation of movable parts can be equal to the sum of each finite element potential energy approximately. And then, the basic motion equations of AC contactor can be got. Nonlinear of geometry, material, friction appears in the motion and bounce of cores and contacts in the closing process. Therefore, the equations can be solved through explicit finite element analysis method.

The contact of deformable objects is always existing in the closing process and the bounce of contactor. Making sure no penetrate happens on the contact surface and considering the friction force between each contact surface, the contact surface should be special handled. Two contacted surfaces are designed as a contact pair. Searching every contact surface of each movable part in the closing process and then calculating the force of each contact pair. Symmetric penalized-function method is applied in to handle contact surfaces: checking penetration between slave nodes and primary surface at every time step in the calculation, if not, nothing is done, or else, a large interface contact force will be induced between the slave nodes and primary surface where penetration happens. The induced penalty function is shown as follows:

$$f_s = -l \times k_1 \times \mathbf{n}_1 \tag{7}$$

where f_s is normal vector of contact force from slave node to contact node, l is penetration depth, $\mathbf{n}_1$ is outer normal unit vector of main surface at the contact point, k_1 is stiffness factor of main surface s_1.Effect of air resistance is ignored in the model. However, the friction force between moveable parts in the closing process must be considered. The friction force is got based on Coulomb equation.

Making f^* as tested friction force, f_n as normal force, k as interface stiffness, μ as friction coefficient, f^n as friction force at the time of n. And then, yield force F_y can be calculated:

$$F_y = \mu \left| f_n \right| \tag{8}$$

Displacement increment Δe of slave node can be calculated:

$$\Delta e = r^{n+1}(\xi_c^{n+1}, \eta_c^{n+1}) - r^{n+1}(\xi_c^n, \eta_c^n) \tag{9}$$

where r is coordinate of main surface, ξ and η are the corresponding coordinate values of main surface. Update the tested value of contact force:

$$f^* = f^n - k\Delta e \tag{10}$$

Making sure of the yield condition:

$$f^{n+1} = f^*,\text{when} \left| f* \right| \leq F^y \tag{11}$$

Adjusting the value of tested force:

$$f^{n+1} = \frac{F_y f^*}{\left| f* \right|},\text{when} \left| f* \right| > F^y \tag{12}$$

The static and dynamic friction coefficients μ_s and μ_d can be smoothed through index difference function. v is relative velocity between slave node and principal piece, friction coefficient can be got:

$$\mu = \mu_d + (\mu_s + \mu_d)e^{-c|v|} \tag{13}$$

$$v = \delta e / \delta t \tag{14}$$

where δ t is time step,c is attenuation constant,μ s and μ d on each contact surface are supplied by manufacturers. Coulomb friction will arouse large interface shear stress, even exceed the maximum stress the material can bear. As several nodes will affect the shear stress and it may surpass the limit value . However, Coulomb friction model makes shear stress is less than the limit value in default. Therefore, the shear stress will be displaced by another limit value:

$$f^{n+1} = \min(f_{Coulomb}^{n+1}, \kappa A_{master}) \tag{15}$$

where $f_{Coulomb}$ is Coulomb friction, A_{master} is area of main surface, κ is viscosity coefficient,and Friction force of each step can be calculated.

2.3. **Calculation flow of 3D dynamic full simulation model of AC contactor.** The model considers the friction between each part and the shape change in the closing process. However, the model needs electromagnetic force as body load and then calculates the velocity and displacement which will affect the result of electromagnetic force. Therefore, electrical, magnetic, mechanical equations of AC contactor should be coupled for solving. Fig.2 shows the coupling flow chart.

Firstly, electromagnetic force at the moment can be calculated through initial displacement, flux linkage, current and so on. Meanwhile, the calculated electromagnetic force will load on the 3D dynamic model. And then, calculate displacement, velocity, acceleration at next moment. If time is not up, return the parameters to the model and calculates the electromagnetic force again and the whole moving process of AC contactor can be calculated. It will not just calculate flux linkage, current, electromagnetic force, but also

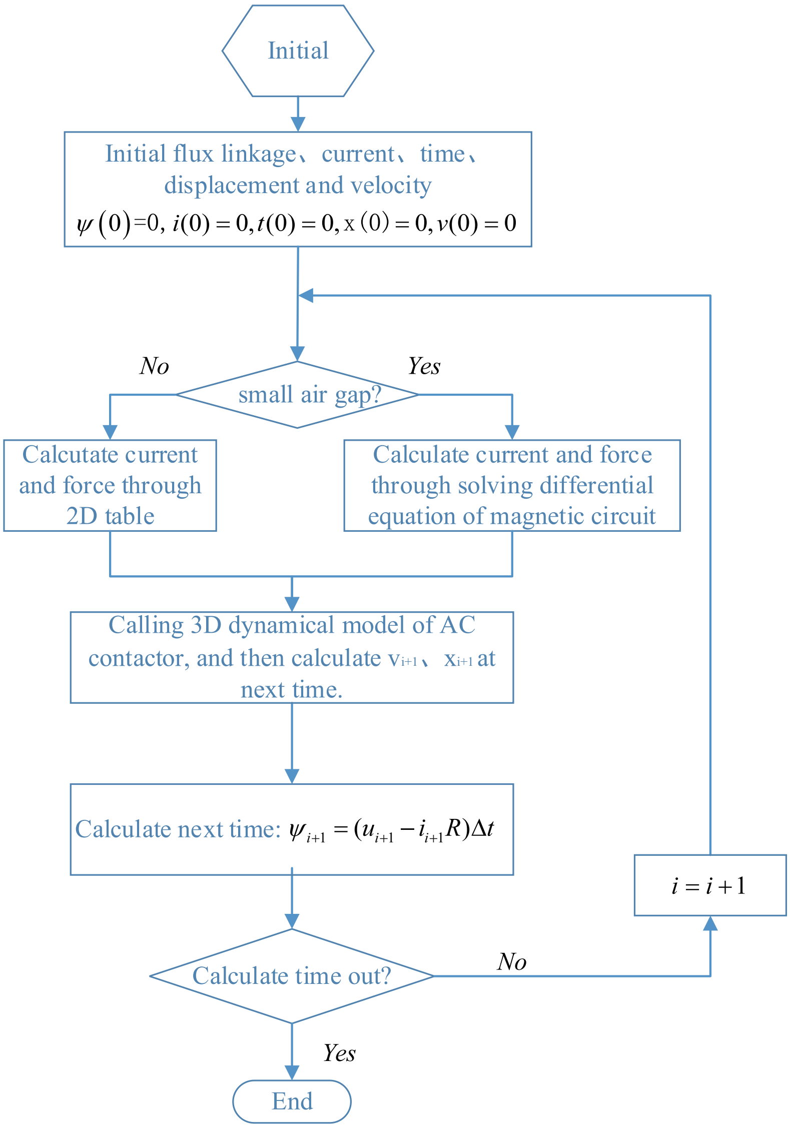


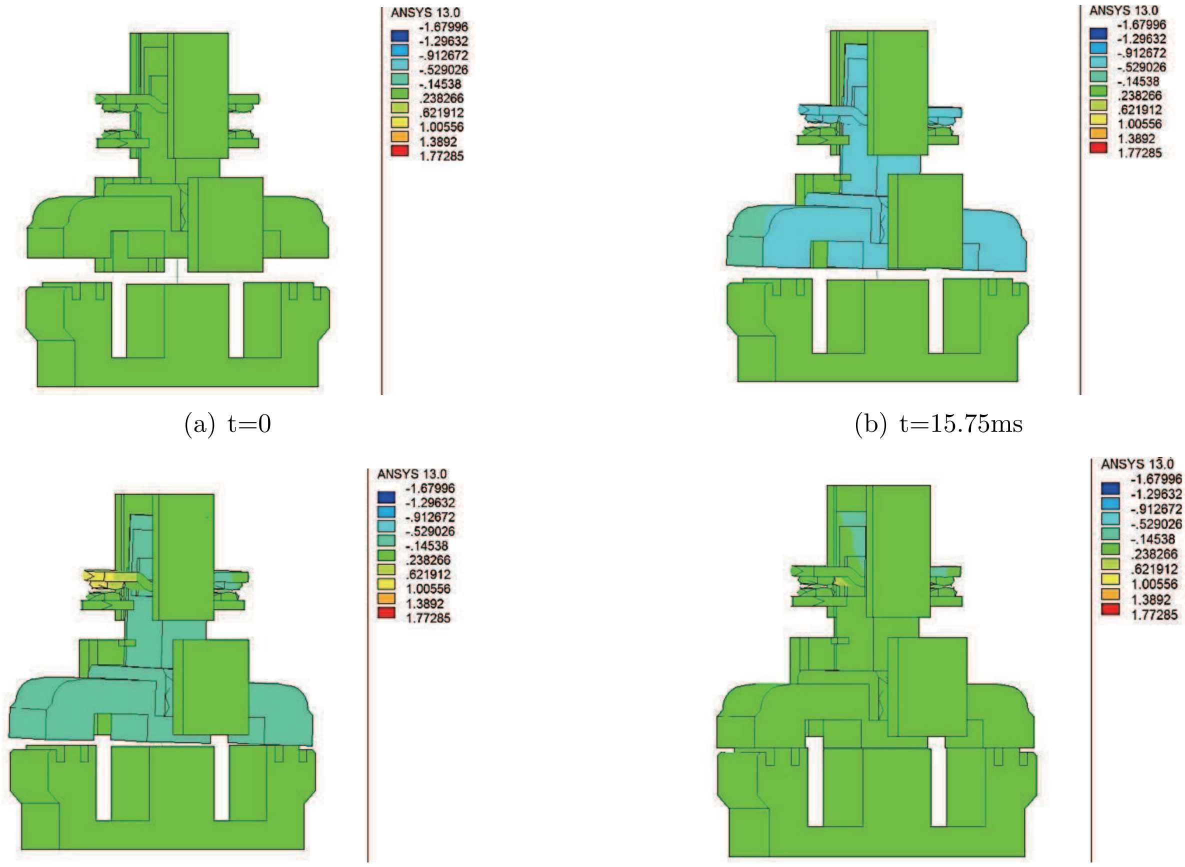
Figure 2. Mechanical model of AC contactor

velocity, displacement, acceleration of contact and core at any point. The bounce signal can be analyzed through the calculated contact displacement.

3. **Simulation results and analysis of AC contactor.** According to the mathematical model above,3D dynamic full simulation model of AC contactor has been built. Setting the input rated voltage 220V, closing phase angle 90°.The 3D moving process of AC contactor at different time is shown in Fig.3.

As shown in Fig.4, the movement paths of contacts and cores can be illustrated intuitively through 3D dynamic full simulation model of AC contactor. It helps the analysis of AC contactor with the variation of parameters, which affect the movement path of contacts and cores. It lays a theory foundation for designing AC contactor with excellent performance. Meanwhile, the design period will be reduced significantly.

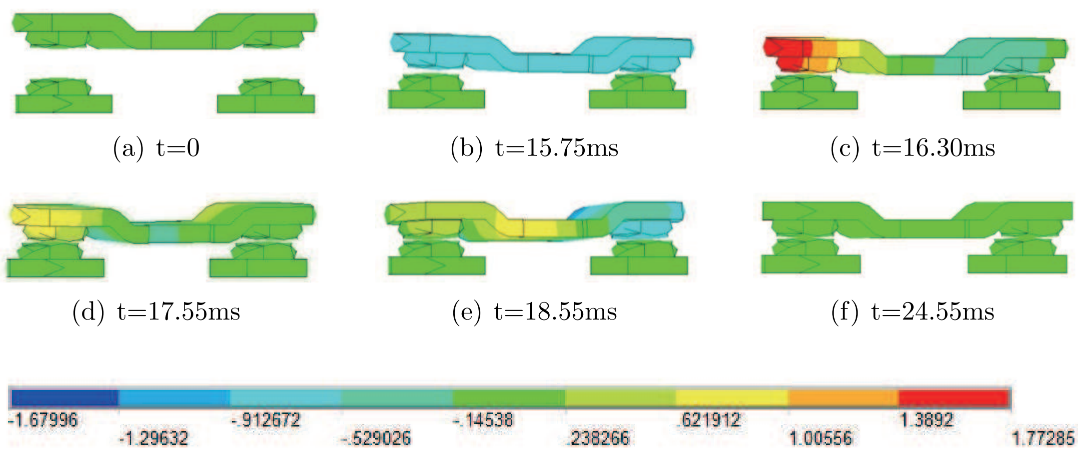
4. **Verification of simulation model.** The dynamic characteristics of AC contactor will be quite different at different closing phase angle θ of electromagnetic system. Through the full simulation model, it can analyze and calculate the dynamic process of contactor at different θ. The accuracy of model should be verified through experiment. The coil



(a) t=0 (b) t=15.75ms

(c) t=17.8ms (d) t=20.15ms

FIGURE 3. Two 3D moving process of AC contactor at different time



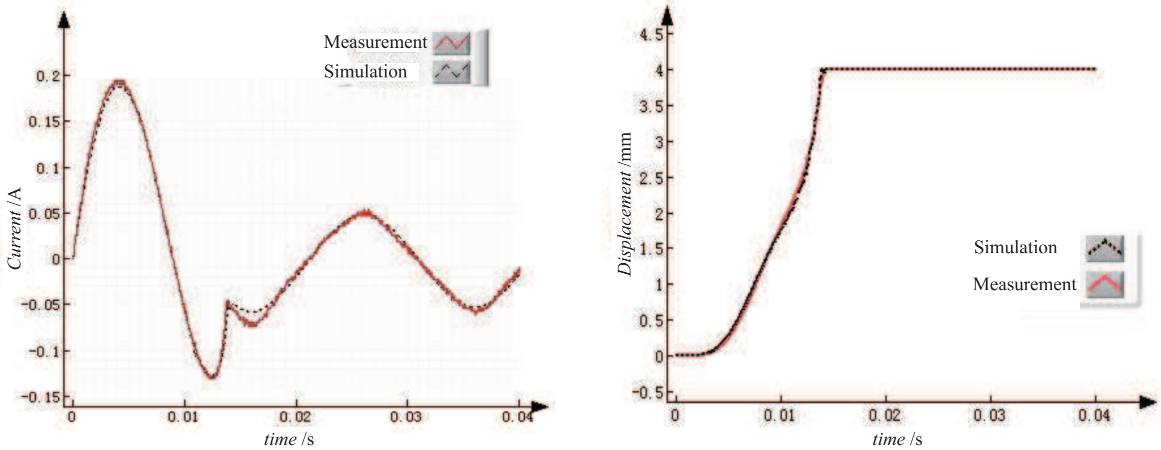
(a) t=0 (b) t=15.75ms (c) t=16.30ms

(d) t=17.55ms (e) t=18.55ms (f) t=24.55ms

FIGURE 4. 3D bounce of contacts in the closing process

current and the displacement of moving core got by simulation and experiment with 230V input voltage and $\theta = 60°$ are shown in Fig.5.The measurement curve is got by using laser displacement sensor.

t_{core} is the closing time of core, i_m is the maximum of relative error point between measurement and simulation current, x_m is the maximum of relative error point between measurement and simulation displacement of core, Re is the relative error, Ae_m is the



(a) Current contrast with at $\theta = 60°$

(b) Displacement contrast at $\theta = 60°$

FIGURE 5. Contrast of simulation and experiment

TABLE 1. Comparisons of simulation and measurement

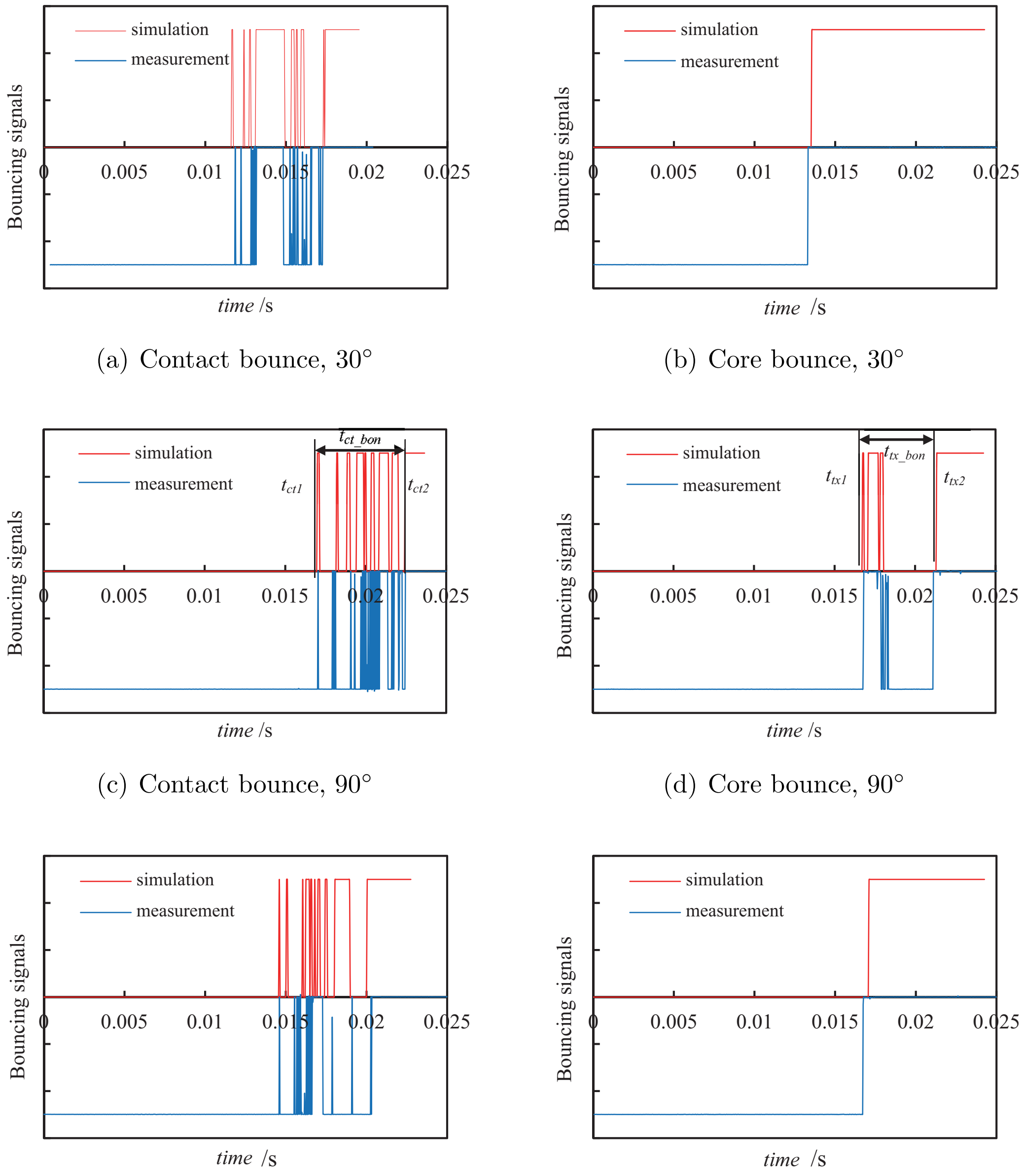
	θ	30°	60°	90°	120°	150°	180°
t_{core}/ms	simulation	14.15	13.95	15.45	19.05	17.25	15.35
	measurement	14.36	13.84	15.40	19.40	17.64	15.64
	relative error/%	0.28	1.16	0.32	1.80	2.21	1.85
i_m/mA	simulation	−74	188	145	98	199	65
	measurement	−79	194	156	107	206	70
	Ae_m	5	6	11	9	7	5
	relative error/%	6.33	3.09	7.05	8.33	3.40	7.14
x_m/mA	simulation	2.80	2.39	3.83	3.57	3.68	3.29
	measurement	2.87	2.51	3.77	3.74	3.82	3.40
	Ae_m	0.07	0.12	0.15	0.17	0.14	0.11
	relative error/%	2.44	4.78	3.98	4.55	3.66	3.23

maximum of absolute error. According to Tab.1, with different θ, the errors of t_{core} are all within 3% ,and the maximum errors of measurement and simulation are all within 9%. The maximum errors of the displacement of core are all within 0.17mm and the relative errors are all within 5%. Therefore, the simulation model can quite really reflect the real dynamic process of AC contactor.

The bounce of contacts and cores,which are very important, should be verified. The comparisons of measurement and simulation with 230V input voltage and different θ are shown in Fig.6.

As shown in Fig.6, the trends of bounce curves are basically consistent, and the bounce interval match well. The bounce with different θ is quite different. According to the contact bounce curves, the time interval between the first contact bounce and the second bounce is quite long, and the contact bounce is quite serious at every θ. Core will not bounce except when $\theta = 90°$. Tab.2 shows the comparisons of bounce at different θ with 230V input voltage.

Tab.2 shows all the relative error in each closing phase angle, the contact first bounce time : within 2%, the contact bounce duration: 5%, the closing time of contact: 2%, the closing time of core: 4%. The bounce of core will happens just when $\theta = 90°$ and the



(a) Contact bounce, 30° (b) Core bounce, 30°

(c) Contact bounce, 90° (d) Core bounce, 90°

(e) Contact bounce, 150° (f) Core bounce, 150°

FIGURE 6. Bounce comparisons of measurement and simulation with different θ

relative error of core bounce time is 6.48%. According to the comparsion, the built 3D dynamic full simulation model of AC contactor can fairy reflect the bounce of contacts and cores.

5. **Conclusion.** 3D dynamic full simulation model of AC contactor applied in air-condition which consists of contact and electromagnetic system is built in this paper. Meanwhile, the model is verified through the measurement,which includes the bounce of contacts and cores. 3D bounce process of contacts and cores can be observed visually by using the model. According to the bounce results of contacts and cores, the measurement and simulation fit well, and the model can fairy reflect the dynamic process. The model can clearly illustrate the 3D moving process of contact and the electromagnetic system. It lays the theoretical foundations for improving the performance of AC contactor. Meanwhile,

TABLE 2. Comparisons of bounce

		θ	30°	60°	90°	120°	150°	180°
contact	t_{ct1}/ms	simulation	11.65	11.95	17.00	16.55	14.60	11.60
		measurement	11.86	12.01	17.04	16.34	14.61	11.64
		relative error/%	1.77	0.50	0.23	1.29	0.07	0.34
	t_{ct_bon}/ms	simulation	5.70	5.80	5.05	6.90	5.45	8.65
		measurement	5.43	5.88	5.07	7.14	5.67	8.55
		relative error/%	4.97	1.36	0.39	3.36	3.88	1.17
	t_{ct2}/ms	simulation	17.35	17.75	22.05	23.45	20.05	20.25
		measurement	17.29	17.89	22.11	23.48	20.28	20.19
		relative error/%	0.35	0.78	0.27	0.13	1.13	0.30
core	t_{xt1}/ms	simulation	13.55	13.65	16.75	18.85	17.10	15.05
		measurement	13.22	13.83	16.82	18.75	16.74	14.61
		relative error/%	2.50	1.30	0.42	0.53	2.15	3.01
	t_{xt_bon}/ms	simulation	0	0	4.60	0	0	0
		measurement	0	0	4.32	0	0	0
		relative error/%	0	0	6.48	0	0	0
	t_{xt2}/ms	simulation	13.55	13.65	21.35	18.85	17.10	15.05
		measurement	13.22	13.83	21.14	18.75	16.74	14.61
		relative error/%	2.50	1.30	1.00	0.53	2.15	3.01

the design period will be reduced significantly. Moreover, it also provides the design idea for virtual prototype design of low-voltage apparatus and the theory basis for the control of AC contactor in the closing process.

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