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Modal Test of Welding Robot Linkage Mechanism

Modal Interval of posture in continuous dynamic state

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***Abstract*—Vibration of welding robot mechanism is an important factor affecting the welding quality. In this paper, a modal test scheme is designed depending on the characteristics of the modal change caused by the posture change during the welding robot operation. In the modal test scheme, the posture used for modal test selects from the dynamic process of continuous posture change. Then the selected posture is tested and the modal parameters are identified. On this basis, we analyze the modal frequency and modal vibration mode of the mechanism under different postures, propose the concept and method of modal interval division, obtain the modal test results of the dynamic continuous process of the welding robot linkage mechanism, and reveal the inherent dynamic characteristics of the welding robot mechanism.**

Keywords—linkage mechanism; parameter estimation; modal experiment; posture division; modal interval

I. Introduction

The welding robot actuator is usually composed of multi-linkage mechanism and is guided by multi-motor to achieve the required motion trajectory[1].When the frequency of the excitation motor is the same or similar to the natural frequency of the mechanism, it will lead to the system resonance, resulting in the increase of the vibration at the end of the robot actuator, which directly affects the welding quality and efficiency of the welded robot[2]. In particular, the mechanism of welding robot is changing in the course of operation, so its modal frequency is also changed within a certain range, which increases the probability of system resonance. Therefore, the modal analysis of the welding robot mechanism plays a major role in improving the welding quality. In this paper, the modal test of the mechanism posture is carried out using LMS, and the modal parameters under the posture change are estimated based on the modal parameter estimation principle. By studying the regularity of modal test results and proposing the concept and method of modal interval division, the modal test results satisfying the dynamic continuous process of welded robot linkage mechanism are presented, which provides a new idea for the study of dynamic system internal characteristics.

II. Method of Modal Parameter Estimation

A. Definition of Modal Parameters

Modal analysis in modal test provides a set of modal parameters that characterize the dynamic characteristics of the structure. These modal parameters can establish the corresponding modal model[3]. For the modal test of welding robot linkage mechanism, a frequency response function (FRF) can be given to describe the test data. The relationship between the modal parameters and the measured values of FRF is shown in equation (1).

$$H_{ij}(\mathrm{j}\omega)=\sum_{k=1}^{N}\left(\frac{r_{ijk}}{\mathrm{j}\omega-\lambda_k}+\frac{r_{ijk}^{*}}{\mathrm{j}\omega-\lambda_k^{*}}\right) \tag{1}$$

$H_{ij}(\mathrm{j}\omega)$ is FRF between response dof i and reference dof j. N is the vibration modal number which affects the dynamic response of the structure in the frequency band. r_{ijk} is the residue of the k-order modal. λ_k is the pole of the k-order modal. The sign * stands for complex conjugate. The value of the pole can be expressed in formula (2).

$$\lambda_k=\delta_k+\mathrm{j}\omega_{dk} \tag{2}$$

ω_{dk} is the damped natural frequency of the k-order modal. δ_k is the damping factor of the k-order modal. The residue can be expressed as the product of the three quantities in equation (3) below. v_{ik} is the k-order modal coefficient of response freedom i. v_{jk} is the k-order modal coefficient of the reference degree of freedom j. a_k is a complex proportion constant, and its value depends on the scale of modal shape. It is worth noting that the modal coefficients can be either real or complex. If it is a real number, the proportion constant a_k can be expressed as formula (4), and m_k is the modal mass of the k-order modal.

$$r_{ijk}=a_k v_{ik} v_{jk} \tag{3}$$

$$a_k=\frac{1}{2\,\mathrm{j}m_k\omega_{dk}} \tag{4}$$

The above parameters, such as the pole, the damped natural frequency, the damping factor, the modal shape and the residue, are the parameters that describe the modal of the structure.

B. Modal Parameter Estimation of Least Square Complex Frequency Domain Method

The basic problem of parameter estimation is to adjust the parameters of the estimation model so that the data estimated by the model is as close as possible to the measured data (through curve fitting). The PolyMax module in LMS Test Lab is used for modal parameter estimation, and the mathematical theory method used by this module is the least squares complex frequency domain (LSCF) method[4].LSCF modal parameter estimation steps are as follows:

1) The mathematical model of matrix fractional is used to fit the measured frequency response function, and a sufficient number of overshoot equations are listed by the selection of frequencies, and the polynomial coefficients of molecular denominator matrices are obtained by least squares estimation.

2) On the basis of the denominator polynomial, the extended friend matrix is constructed and the eigenvalue of the friend matrix is decomposed, so that the pole and modal participation factors of the system are obtained.

3) The modal vibration pattern can be analyzed and solved in the mathematical model of matrix fractional generation of matrix polynomial coefficients. PolyMax is more convenient to solve modal modes directly by using the least squares frequency domain method (LSFD).

4) In order to prevent the introduction of false mode or the loss of real mode, the modal safety criterion (MAC) was used to verify the modal parameters after the completion of modal test.

III. EXPERIMENTAL

A. Test System Composition and Test Scheme Design

Combined with the structural features of welding robot, the corresponding test system is built, which mainly includes five parts: welding robot test bench, posture control system, excitation system, spectrum acquisition system and modal analysis system. The single point excitation multi-point response (SIMO) method is adopted to test, that is, to fix the hammer striking point, and all acceleration sensors are on the measured parts to test the transfer function, so as to carry out experimental modal analysis or transfer path analysis.

The test scheme takes the welding robot mechanism part as the test object, the control system operation to the test posture, the Force Hammer (LMS 086c03) to collect the excitation signal, the PCB acceleration three-direction sensor (ICP 365A25 series) on multiple measuring points to collect the acceleration signal. The transfer function between the excitation point and the measuring point can be analyzed by using the excitation signal and the vibration acceleration signal obtained by LMS Test lab system. Finally, the modal information of the measured structure is extracted by PolyMax. Test site and scheme are shown in Figure I and Figure II above.

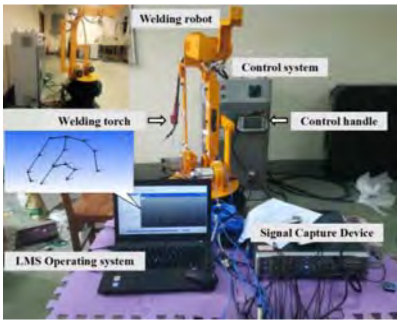

FIGURE I. TEST SITE

FIGURE II. TEST SCHEME

B. Test Posture Selection and Signal Acquisition

The experimental modal parameters focus on the modal of the whole continuous welding process instead of the single posture. Since the welding track planning of this test is the process of drawing a circle with diameter of 15cm, the welding gun head is centered on a fixed position and draws a circle with equal radius. There is a linkage between the mechanism rods, and the change of movement and rotation between the multiple rods will change the modal. The motion posture of the robot linkage mechanism is operated by the operation handle of the active control system, and the robot is stopped for modal testing under selected postures.

The control procedure of welding drawing circle of welding robot is divided into two stages (pre-welding preparation stage and welding stage). In the pre-welding preparation stage, the six-bar mechanism rotates with the big arm and the welding gun arm also rotates, so that the welding torch head from the horizontal 0° to perpendicular to the horizontal plane 90° before welding. This process takes three test postures, respectively, is the welding gun corner 0°, welding gun corner 45° and welding gun corner 90°. In the whole process of welding, the welding gun can draw a circle on the horizontal surface under the joint action of each bar. In this stage, the trajectory of the welding drawing circle can be truncated to six equal parts. The truncation points correspond to six test postures during the welding drawing circle, which are 0° (360)° of drawing circle, 60° of drawing circle, 120° of drawing circle, 180° of drawing circle, 240° of drawing circle and 300° of drawing circle, as shown in Figure III and Figure IV.

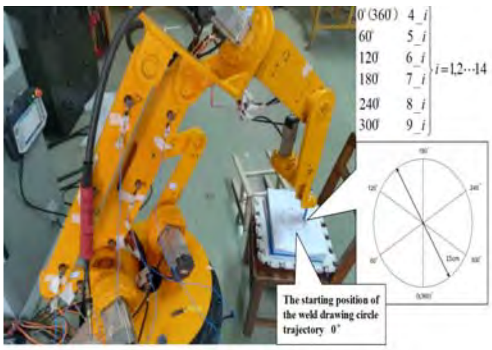

FIGURE III. WELDING TORCH HEAD POSITION UNDER WELD CIRCLE TEST POSTURE

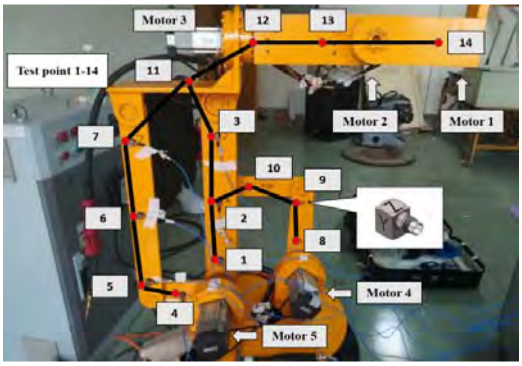

FIGURE IV. LOCATION OF POINT 1-14 AND EXCITATION POINT DISTRIBUTION

Considering that the number of front-end channels for signal acquisition is limited (the number of front-end SCADAS SCM05 has 24 channels), the number of test points and the three-way sensor need to occupy more channels, so this test uses the same posture multi-batch measurement method. Select the measuring point 2 position as the excitation point and apply the Hammer pulse along the X negative direction. The same posture is divided into two batches of testing, the pre-welding preparation stage of the three test posture set to posture 1-posture 3, the welding phase of six test posture set to posture 4-posture 9, geometric modeling as shown in Figure V and Figure VI.

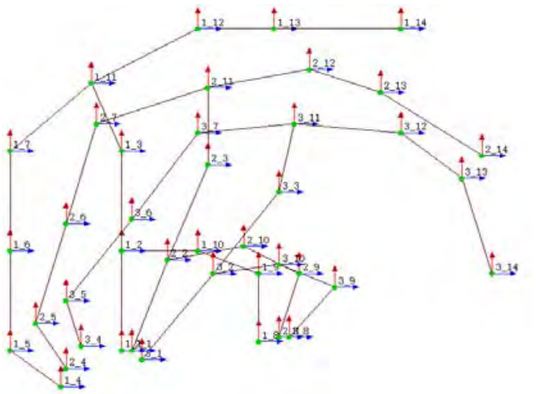

FIGURE V. POSTURE 1-POSTURE 3 GEOMETRIC MODELING

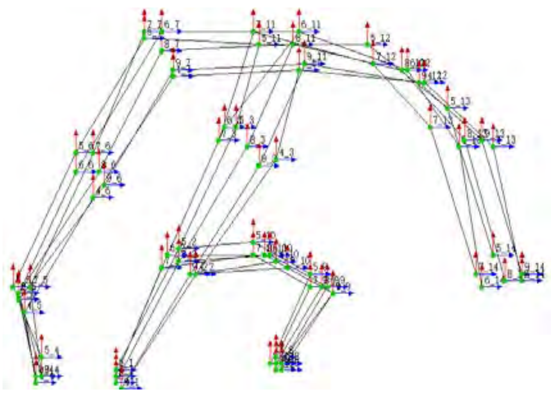

FIGURE VI. POSTURE 4-POSTURE 9 GEOMETRIC MODELING

C. *Modal Parameter Identification and Validation*

The steady state graph of posture 1 is obtained by using PolyMax method (least squares complex frequency domain method) to solve the coefficient matrix, as shown in Figure VII.

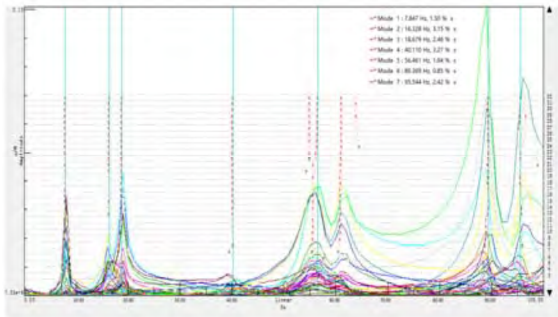

FIGURE VII. STEADY STATE DIAGRAM OF POSTURE 1

TABLE I. MODAL TEST NATURAL FREQUENCY AND DAMPING RATIO OF POSTURE 1

modal	*Natural frequency (Hz)*	*Damping ratio(%)*
1	7.847	1.50
2	16.328	3.15
3	18.679	2.46
4	40.110	3.27
5	56.461	1.94
6	89.369	0.85
7	95.544	2.42

Modal confidence criterion (MAC) is used to test the correlation of modal vectors[5][6]. The MAC value of the same modal vector to itself is infinitely close to 1, and the MAC value of two vectors of different modals (adjacent modals) should be less than 20% to meet the orthogonal requirements of modal vectors. The correlation definition of modal vectors is shown in formula (5).

$$\mathrm{MAC}(\{\psi\}_r,\{\psi\}_s)=\frac{\left|\{\psi\}_r^{*T}\{\psi\}_s\right|^2}{\left(\{\psi\}_r^{*T}\{\psi\}_r\right)\left(\{\psi\}_s^{*T}\{\psi\}_s\right)} \qquad (5)$$

The MAC diagram of posture 1 is shown in Figure VIII, and the results show that the different modal vectors of posture 1 meet the orthogonal requirements.

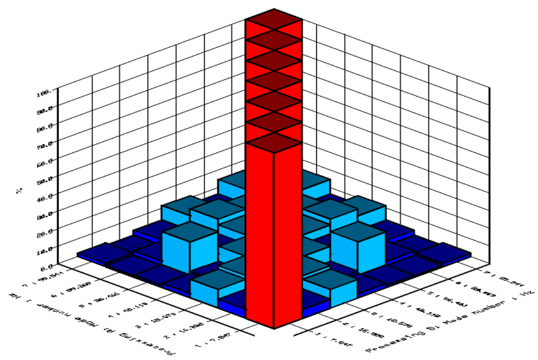

FIGURE VIII. POSTURE 1 MODAL SAFETY CRITERION (MAC) DIAGRAM

The 7-order modal of posture 1 is determined by the above results, and the modal vibration pattern corresponding to the 7-order modal can be solved by using PolyMax. Among them, the vibration type is dynamically displayed, and the phase of the vibration type is divided into phase:0-360°.The results of the first 4-order modal vibration pattern corresponding to the phase:90° are shown in Figure IX.

1-ORDER 2-ORDER

3-ORDER 4-ORDER

FIGURE IX. THE FIRST 4-ORDER MODAL VIBRATION RESULTS OF POSTURE 1

According to the method of modal parameter identification and verification of posture 1, the modal frequency of posture 2-posture 9 is obtained by the same way. The modal frequencies of the 9 test postures selected by the welding robot linkage mechanism are shown in Table II.

TABLE II. THE NATURAL FREQUENCY OF EACH ORDER IN THE MODAL TEST OF POSTURE 1-POSTURE 9

Frequency/Hz	*Posture1*	*Posture2*	*Posture3*	*Posture4*	*Posture5*	*Posture6*	*Posture7*	*Posture8*	*Posture9*
Mode 1	7.847	8.514	9.415	10.072	10.311	10.043	9.902	9.902	9.791
Mode2	16.328	15.761	16.504	11.918	13.240	13.074	15.420	17.142	17.263
Mode 3	18.679	17.185	17.376	17.122	18.044	15.954	17.791	63.403	35.262
Mode 4	40.110	38.866	37.105	18.084	18.844	42.751	35.278	83.476	41.867
Mode 5	56.461	52.435	42.683	35.276	24.794	95.117	42.808	87.200	62.502
Mode 6	89.369	85.487	52.658	42.432	42.709		62.360		83.240
Mode 7	95.544	92.358	83.801	63.474	52.356		83.243		86.882
Mode 8				83.532	63.325		88.727		
Mode 9				89.049	83.284				
Mode 10					96.223				

IV. DIVISION OF MODAL INTERVALS

The natural frequency change of the first-order modal with posture 1 to 9 is obtained from Table II as shown in Figure X.

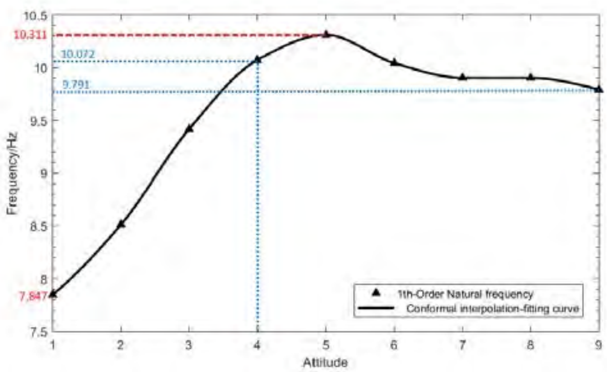

FIGURE X. VARIATION OF FIRST ORDER NATURAL FREQUENCY WITH POSTURE IN A WELDING WORKING CYCLE

Figure V and VI show that the posture change amplitude of posture 1-3 is larger than that of posture 4-9 during a welding working cycle. Combined with the results shown in Figure X, the change range of the first order natural frequency in a working cycle is 7.847hz-10.311hz, in which the first order natural frequency of the pre-welding preparation stage is increasing, the frequency change difference is $\Delta f = 2.225$, and the difference of the natural frequency change of the first order in the welding circle stage is $\Delta f = 0.52$.Therefore, the natural frequency changes with the change of posture, and the greater change of posture amplitude, the wider natural frequency fluctuation range. For the dynamic process of the whole welding operation, the expression of the modal frequency is no longer a single value, but a numerical interval. Therefore, the first order natural frequency interval of the continuous dynamic process of posture 1-9 is [7.847, 10.311], wherein the first order natural frequency interval of the dynamic process of the welded circle is [9.791,10.311].

The natural frequency of the same order modal of different postures in continuous dynamic process is expressed in the form of modal interval, in which the posture of all modals in this interval is planned according to the welding trajectory. The modal vibration mode corresponding to any stationary posture should be similar to the modal modes of other postures in the interval. Under different postures, the position and vibration displacement of the measuring point are different, but the vibration mode is the same on the corresponding phase. The correlation test of modal vectors with different postures of the same order is carried out by using the modal determination criterion MAC (Formula 5) to verify whether all modes in different postures in the modal interval belong to the same order. Figure XI below is the first-order modal vibration pattern of posture 1-9 when the phase is 90°. When the vibration pattern satisfies the similarity requirement, and the MAC value is greater than 40% through the solution of formula 5, it can be considered that the modal modes of these vectors are similar, the modal frequency is the same or similar, belonging to the same modal interval.

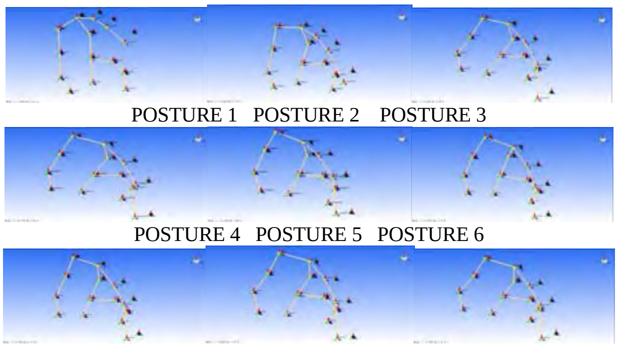

FIGURE XI. PHASE 90° OF FIRST-ORDER MODAL MODE OBTAINED BY POSTURE 1-9

According to the above modal 1 interval expression, for a welding working period of the modal changes, compared to a single posture in the modal order of the 1 order, 2 order, 3 order, etc., the continuous dynamic posture to set the modal interval of 1 interval, 2 interval, 3 interval and so on. Each order corresponds to a modal frequency, and by the same token, each interval corresponds to a modal frequency interval. The criterion of modal interval division is defined according to modal determination criterion (MAC value): for two vectors of the same order, its Mac value is 100%, and for multiple vectors of the same interval, when the Mac value is greater than 40%, it can be considered that the modal modes of these vectors are similar, the modal frequency is the same or similar, belong to the same modal interval. The modal frequency interval obtained by the sample posture (posture 1-9) is defined as all modal frequency values in the frequency domain of a continuous process that covers an infinite attitude change during a welding working cycle.

The division method of modal interval:

1) According to the steady state diagram of posture 1-9, all modes of 9 postures are counted. In order to prevent the loss of real modal and ensure the accuracy of modal interval division, the modal determination criterion is not verified for the time being. The statistical modal frequency and the preliminary division of the modal interval are shown in able 3, and each row in the table corresponds to a preliminary interval.

2) The modal parameters of posture1-9 are verified by MAC, and the natural frequency results after each posture verification are shown in bold in Table III, which is consistent with the results in Table II.

3) Coordinate 9 postures, the 9 test posture as the overall division interval, and the natural frequency of the bold in the table as the standard, when there is a posture of the longitudinal adjacent two lines of the natural frequency are bold, that is, the two intervals belong to different modal, can be judged by the similarity of vibration and MAC value further verification. It is considered that these 2 intervals belong to different modal intervals for the whole dynamic process. such as Mode2 and Mode3, under posture 6, its 2-order natural frequency and 3-order natural frequency vibration similarity is less than 20%, so for posture 6 is not as the same order modal. For dynamic processes, these two-order modals belong to two modal intervals respectively, so they are divided into different two modal intervals, and the modal vibration similarity of different modal intervals is less than 40%. Similarly, the modal similarity of any posture in the initially divided interval in Mode 9 is greater than 20%, so that the two initially divided intervals can be merged into one interval, which is the 9 Interval of the dynamic process. The interval partitioning results are shown in Table III.

TABLE III. MODAL FREQUENCY INTERVAL PARTITION

Frequency/Hz	*Posture1*	*Posture2*	*Posture3*	*Posture4*	*Posture5*	*Posture6*	*Posture7*	*Posture8*	*Posture9*	*Frequency interval/Hz*
Mode 1	**7.847**	**8.514**	**9.415**	**10.027**	**10.311**	**10.043**	**9.902**	**9.902**	**9.791**	[7.847,10.311]
Mode2				**11.918**	**13.240**	**13.074**		11.217		[11.217,13.240]
Mode 3	**16.328**	**15.761**	**16.504**			**15.954**	**15.420**			[15.420,16.504]
Mode 4		**17.185**	**17.376**	**17.122**	**18.044**	18.013	**17.791**	**17.142**	**17.263**	[17.122,18.044]
Mode 5	**18.679**			**18.084**	**18.844**					[18.084,18.844]
Mode 6			24.316		**24.794**					[24.316,24.794]
Mode 7	**40.110**	**38.866**	**37.105**	**35.276**	35.141	35.597	**35.278**	35.115	**35.262**	[35.115,40.110]
Mode 8		46.313	**42.683**	**42.432**	**42.709**	**42.751**	**42.808**	41.721	**41.867**	[41.721,46.313]
Mode 9	54.904	**52.435**	**52.658**	53.036	**52.356**	52.476	53.140	53.127	53.372	[52.356,56.461]
	56.461	55.850				56.219	55.485		56.000	
Mode 10	61.069	61.987	63.594	**63.474**	**63.325**	62.058	**62.360**	**63.403**	**62.502**	[61.069,65.554]
	63.880								65.554	
Mode 11		79.761		80.135		80.323				[79.761,85.487]
		85.487	**83.801**	**83.532**	**83.284**	82.163	**83.243**	**83.476**	**83.240**	
Mode 12	**89.369**	86.573	88.984	**89.049**	89.325	89.190	**88.727**	**87.200**	**86.882**	[86.573,96.223]
		92.358	93.277	94.157		92.580	92.291	93.522	93.332	
	95.544		95.526	95.523	**96.223**	**95.117**	96.674	95.458	94.990	

As can be seen from Figure V, VI and X above, the posture of the linkage mechanism 1 to 3 has a large range of changes, and the deviation amplitude of the natural frequency in the interval has a large range of modal ranges. Posture 4-9 is in the process of drawing circles by welding. Although the linkage between the mechanism bars is complex when drawing circles by welding, the range of posture change is not large, so the range of modal frequency range is relatively small. The pre-welding preparation stage and the welding stage of the robot were divided into the modal frequency intervals according to the division method of the modal interval. The results are shown in Table IV.

TABLE IV. MODAL FREQUENCY INTERVAL DIVISION OF POSTURE 1-3 AND POSTURE 4-9

Frequency interval/Hz	*posture 1-3*	*Δf*	*Frequency interval/Hz*	*posture 4-9*	*Δf*
Mode 1	[7.847,9.415]	1.568	Mode 1	[9.791,10.311]	0.520
Mode2	[15.761,16.328]	0.567	Mode2	[11.217,13.240]	2.023
Mode3	[17.185,18.679]	1.494	Mode3	[15.420,15.954]	0.534
Mode4	[37.105,40.110]	3.005	Mode4	[17.122,18.044]	0.932
Mode5	[42.683,46.313]	3.630	Mode5	[18.084,18.844]	0.760
			Mode6	24.794	0.000
Mode6	[52.435,56.461]	4.026	Mode7	[35.115,35.597]	0.482
			Mode8	[41.721,42.808]	1.087
Mode7	[79.761,85.487]	5.726	Mode9	[52.356,56.219]	3.863
			Mode10	[62.058,65.554]	3.496
Mode8	[86.573,96.223]	9.650	Mode11	[80.135,83.532]	3.397
			Mode12	[86.882,96.223]	9.341

V. CONCLUSION

(1) The division of modal interval can clearly express the influence of mechanism posture change on natural frequency, the order of system modal, frequency, damping and other system characteristics will change with the change of posture. Because of the complexity of posture change itself and the existence of multiple orders in a modal, the change of natural frequency does not have clear regularity research conditions. The form of modal interval division can indicate the system characteristics of the linkage mechanism under dynamic conditions such as the whole working cycle, the preparation stage before welding and the welding stage.

(2) In the continuous dynamic process of the linkage mechanism, the absence of modal in the same order shows that the change of posture has an effect on the modal. It is also shown that if modal resonance occurs, it may only occur at a certain stage or in certain postures of a continuous process.

(3) For the determination of modal interval division, the higher the interval, the range of modal interval is larger than that of the first few intervals. The more obvious the natural frequency in the same modal interval is affected by posture change. Therefore, the division of modal interval is generally selected in the first 4 interval-5 interval is more accurate, its Δf is generally in the range of 1Hz to 2Hz, can be simplified to think that the same frequency. For the interval height of the modal interval, its Δf is generally 3Hz to 9Hz, or even larger. At this time, the modal interval accuracy and interval boundary conditions are not guaranteed, and the corresponding confidence interval can be set as the boundary condition of the interval.

(4) The modal posture of the same modal interval is different and the vibration pattern is similar. The modal of different postures in the same modal interval also uses the modal determination criterion MAC to test the correlation of modal vectors, which is consistent with the modal parameter verification of stationary posture. The MAC value setting of different modals under a single posture is less than 20%, and the MAC value setting of different postures in the same modal interval is greater than 40%.

The results of modal interval division and the method of modal interval division are summarized in regularity, and the applicability of modal interval division method to the study of dynamic system performance is verified, which provides a basis for the research and improvement of dynamic characteristics of welding robot linkage mechanism.

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