Research Article

A Nonlinear Vibration Compensation Method for Engineering Forging Hydraulic Press Using Tabu Search Algorithm

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The research on the nonlinear vibration compensation method in the field of forging hydraulic press is still in the blank stage. This paper studies the nonlinear vibration compensation problem of forging hydraulic press under the action of a kind of nonlinear external system and realizes the increase of a kind of nonlinear vibration in the nonlinear system of a hydraulic press. This paper proposes two methods to solve the nonlinear relationship. One is to concatenate an inverse function of a nonlinear relationship and synthesize it to obtain a linear relationship. While another is to acknowledge its nonlinear relationship and determine its output based on its nonlinear relationship. Furthermore, this paper chooses the tabu search algorithm to solve the compensation problem of nonlinear vibration and improves its search neighborhood to solve the problem of vibration range selection, analyses the vibration reinforcement calculation, and describes the specific steps of applying the tabu search algorithm. Finally, MATLAB is used to simulate and validate the designed method. The simulation results show that the method can suppress nonlinear vibration and the corresponding compensation effectiveness, proving the design method’s rationality.

1. Introduction

Hydraulic presses are a type of machine tool that is extensively used in many companies, including automotive, aviation, and agricultural machinery. Fluid under pressure is used in a hydraulic press to generate, transmit, and imply pressure. The hydraulic press must finish a cycle of acceleration, reducing in fast traverse power, a having to work stroke, stress holding, adequate rest, a slow return stroke, and emerged as a way stroke, decelerating, and stopping during the pressing and trying to form process. It is important to follow a predefined path during a tool is applied [1]. The hydraulic press’s electrohydraulic scheme, on the other hand, is nonlinear and subject to no smooth or disjointed nonlinear effects, including a nonlinear pressure-flow interaction, dimensional change of nozzle, friction nonlinearity, or external disturbances. The external load on a hydrodynamic press’s electrohydraulic system as well involves a significant unidentified parameter [2]. Despite the advancement of innovative control methods over the last few decades, the proportional-integral-derivative (PID) control system is still the industry’s most widely applied technique due to simplicity, stable operation, and good firmness. A PID controller evaluates the current control error (P), the previous control error (I), and the predicted future regulate error (D). It mimics the natural responses of humans to external stimuli [3, 4]. Many advanced controllers have been proposed to this point, which has achieved good control performance and can be especially in comparison to a traditional PID controller. In practice, linear systems do not exist since all physical systems are nonlinear to a certain large extent [5].

Because of the above, many scholars have worked to improve the performance of hydraulic presses. In this regard, the speed of the forging hydraulic press is controlled using the back-step recursion method in the work of [6]. They investigated the nonlinearity and time-varying nature of the hydraulic press model during their work. In addition, the mathematical model of the single-cylinder hydraulic press is built, the Lyapunov function is built on top of this
model, and the hydraulic press speed is solved using reverse recursion. They demonstrated the system’s stability using a nonlinear control mechanism. Furthermore, simulation is used to verify the tracking effect of the control mechanism on both constant and time-varying speeds. As a result, their proposed model has overcome the single-cylinder hydraulic press system’s nonlinearities. Apart from the above, an adaptive control based on the back-step recursive approach is used in some works of literature [7]. During their work, they first assess the hydraulic press model based on physical features and then develop the speed controller based on this model using the back-step recursive method. Finally, a genuine hydraulic model is used to verify the designed control law. Their simulation findings suggest that the control rule can effectively tackle the system’s nonlinear and speed tracking issues. To solve the above shortcomings, some researchers [8] have used the Lyapunov direct method to realize the position tracking control of the single-cylinder hydraulic press. The control law and related approaches are explained after they generate a simplified form of the Lyapunov function. Taking the ultralow speed forging hydraulic press system as a simulation example, their simulation results confirm the effectiveness of the adopted control law. However, the control of a multicylinder hydraulic machine is much more complicated than that of a single-cylinder hydraulic machine. It is also necessary to consider issues such as leveling, synchronization, and servo. There are also many factors such as unknown loads and parameters that cause the complexity of its control. For the sake of the aforementioned, there is a need for an optimization technique to overcome these shortages.

Tabu search is an optimization technique based on memory [9]. It is a problem-solving method based on metheuristics that are used to overcome complex optimization problems. The authors of [9] proposed it first, and scholars of [10] expanded on it. TS has earlier been applied to a wide variety of optimization problems, including traveling salesman problems [11], global optimization of artificial neural networks [12], and telecommunication networks [13]. With the latest work report by [14, 15], TS is just starting to see the implementation to the energy industry. Tabu search is an effective method for optimizing a multiparameter framework that can produce excellent results. Even though the application is not simple and necessitates tuning, once formed, it is able to solve a wide range of problems. This technique is most suitable for the nonlinear vibration compensation method especially in engineering forging hydraulic press. As mentioned above, the control methods for hydraulic presses can be mainly divided into the following categories: PID control strategy and its deformation, sliding mode control strategy, back-stepping control strategy, adaptive control strategy, etc. Several methods are combined [16]. It can be seen that there is no precedent for the application of nonlinear output adjustment methods in the hydraulic field among the current nonlinear vibration compensation methods for hydraulic systems in the United States and abroad. As a result, the main content of their work is still in the early stages of research. The purpose is to open up a new direction for the research of nonlinear vibration compensation in the hydraulic field, to play a role in the follow-up research. This paper introduces the first controlled object, the forging hydraulic press, and illustrates the development of nonlinear control methods as well as nonlinear output regulation theory in the field of a hydraulic press. In addition, it suggests two approaches for resolving the nonlinear relationship. The first is to concatenate an inverse function of a nonlinear relationship and synthesize it to obtain a linear relationship. The second is to acknowledge its nonlinear relationship and determine its output based on its nonlinear relationship. In addition, it selects the tabu search algorithm for further solving the compensation problem of nonlinear vibration and improves its search neighborhood to solve the problem of a vibration range selection. It analyzes the vibration reinforcement calculation and the specific steps of applying the tabu search algorithm. The remaining of the contributions of this research are numbered below:

1. It introduces the definitions and theorems related to stability that are used in the research of nonlinear output regulation theory

2. It studied the nonlinear output regulation control procedures for the class of nonlinear external systems; in addition, it introduces state feedback control laws for nominally affine nonlinear systems, besides the construction of the nonlinear internal system, the functions used in the construction of the nonlinear internal model, and the construction of the nonlinear internal model equation

3. Four assumptions are made, as well as the corresponding nonlinear internal model and state feedback control of the entire composite system; the design of the law also proves that the designed method meets the requirements of system stability and output regulation characteristics

The remaining of the paper is organized as follows: second section explains nonlinear characteristics and nonlinear compensation, third section explains our proposed tabu search algorithm and its optimization, fourth section consists the results of our experimental work and simulations, and fifth section concludes our paper.

2. Research on Nonlinear Characteristics and Nonlinear Compensation

A set of linear equations describes the relationship between two variables, whereas a straight line frequently describes the relationship curve between the input and output variables. At this point, the two variables are called a linear relationship. If the relationship between two variables cannot be described as linear, then they are nonlinear according to

\[
\begin{align*}
\ddot{x}_1 &= a_1x_1 + a_2x_2 - T, \\
\ddot{x}_2 &= b_1x_1 + b_2x_2 \sqrt{P_x - x_2}, \\
\ddot{x}_3 &= c_1x_3 + c_2u.
\end{align*}
\]
Linearity is used to determine whether the relationship between the input and output of a link, process, or system is linear. The relationship between the input and output is called the characteristic curve. The linearity of the sensor is defined as the maximum deviation of the actual average characteristic curve of the forward and reverse strokes relative to the reference straight line, expressed as a percentage of the full-scale output. For different reference curves, there may be different linearity. The linear relationship is a relationship that meets the specified error within a certain input variable and output variable range. Changing the reference straight line can change the linearity of the input-output relationship. Therefore, linearity can be divided into independent linearity, end-base linearity, zero-base linearity, etc. Usually, the least squares method is used to fit the actual characteristic curve to minimize the sum of squares of errors at each point. Change the range of the input variable, and the linearity of the input-output relationship will also change accordingly. Changing the accuracy requirements of linearity can also make the characteristic curve nonlinear. If a mathematical model of the input-output connection is created, the output under a known input signal can be directly determined by the mathematical model, solving the nonlinear problem. This has important implications for current smart applications as described in [17].

\[
\begin{align*}
\bar{x}_1 &= a_1x_1 + a_2x_2 - T, \\
\bar{x}_2 &= b_1x_1 + b_2x_3 + P_i - x_2, \\
\bar{x}_3 &= c_1x_3 + c_2(u - v(w)).
\end{align*}
\]

For nonlinear characteristics, the early method is to keep a distance, usually reducing detection or control accuracy and narrowing the application range, or treating nonlinear characteristics as linear characteristics. However, with the improvement of the detection and control accuracy requirements of the process and the expansion of the application range, the use of linear approximation often cannot meet the application requirements. At present, due to the application of digital technology, it has been possible to face nonlinear characteristics, that is, to correctly apply nonlinear mathematical models and study various methods of nonlinear compensation. Here, the development of computer technology and software technology provides effective means and tools for the compensation of nonlinear characteristics, which means that the study of nonlinear compensation has practical application significance. All in all, it is no longer necessary to keep a distance from nonlinear characteristics, but according to the requirements of engineering applications, we can face its nonlinear characteristics directly, adopt modern digital technology and computer technology, apply mathematical models describing nonlinear characteristics, and realize nonlinear compensation.

2.1. Types and Effects of Nonlinear Properties. Nonlinearity is the behavior of a circuit, particularly an amplifier, in which the strength of the output signal is not proportional to the strength of the input signal [17]. The ratio of output to input amplitude (also known as gain) in a nonlinear device is affected by the strength of the input signal. The input and output relationships of the actual process are mostly nonlinear relationships. Types of nonlinear properties can be illustrated by Figure 1.

2.1.1. Saturated Nonlinear Characteristics. Saturation is a word used to denote a curve’s sophistication. Although this may appear unequal, the saturation of a curve can be numerically solved. As a result, a saturated function has been mathematically smoothed out. The term “saturation nonlinearity” refers to the fact that the output signal does not increase linearly as the input signal increases but instead slows down. Simply put, the linear region within the input limits is the nonlinearity factor of saturation. When the input exceeds this threshold, the output is permanent. Saturation nonlinear properties can be obtained from

\[V(w) = \frac{1}{2}w_1^2 + \frac{1}{2}w_2^2.\]

2.1.2. Dead-Band Nonlinearity. Dead-band is a type of hard nonlinearity that frequently occurs in many controllers of industrial systems, particularly those containing basic ingredients like hydraulic or pneumatic valves and electric motors. Dead-band features are frequently unidentified, and it has already been demonstrated that their existence can significantly reduce control system results in restriction loops in a closed-loop system. The dead-band is a nonlinear characteristic in that the output does not occur or changes very little when the small-amplitude input signal changes. The dead-band nonlinearity can be calculated by utilizing

\[\frac{dV}{dt} = \frac{1}{2}w_1^2 - \frac{1}{3}w_1^4 \leq 0.\]

2.1.3. Different Gain Nonlinearity. When control strategies require control signals with only two or three conditions, different gain nonlinearities are frequently used in control systems. The relay can be in one of two positions for input current between two switching instances, depending on the previous date of the input. This feature is known as on/off, and it contains a certain amount of dead zone in practice. Because different gains require a different amount of current to move the armature, there is a dead zone. In simple words, similar to the dead zone is the differential gain nonlinearity. The different gain nonlinearity can be calculated utilizing

\[\theta^{e+1} = \theta^e + \alpha \left(\frac{X}{B}\right)^T \left(X^B\theta^e - y^B\right).\]

2.1.4. Signal Quantization. Nonlinear quantization can be achieved by passing signals through a compressor circuit, which enhances the signal’s weak elements while decreasing its strong elements. Since computers are widely used in industrial production processes, analog signals must be quantized into digital quantities. The signal quantization
can be calculated by utilizing
\[ r(x) = \begin{bmatrix} x_1 + x_3 \\ x_2 - x_4 \end{bmatrix}. \]  
(6)

2.1.5. Modulation. Nonlinear modulation behaves like a nonlinear system: the modulated signal’s bandwidth is wide and can be varied depending on the ratio of the two spectral components of the modulating signal. Similar to signal quantization, modulation techniques that modulate analog signals into digital signals also introduce nonlinear properties.

\[ K = \frac{\partial r}{\partial x} g(x). \]  
(7)

2.1.6. Bang-Bang Control. In the nonlinear control system, the shortest time control system is adopted, which is called bang-bang control. It is a nonlinear control system, which defines a hysteresis band, the feedback signal is above the hysteresis band, the controlled system operates in one phase, and the feedback signal is lower than the hysteresis band. Here, the controlled system operates in another phase. The bang-bang control can be calculated by using
\[ \bar{x} = f(x) + g(x)u. \]  
(8)

2.1.7. Effect of Nonlinearity Such as Zero Drift and Drift Caused by Different Working Conditions. It changes in input and output characteristics due to changes in working conditions or aging of components. This can be calculated by
\[ a(x) = -10(x_1 - x_{1d}) - 50 \int (x_1 - x_{1d}) dt. \]  
(9)

2.2. Nonlinear Compensation. When the detection and control accuracy requirements are not high, nonlinear compensation can usually not be used. With the improvement of production process detection and control accuracy requirements, some original nonlinear problems are exposed, and some new systems require higher accuracy requirements [18]. Therefore, nonlinear compensation becomes more and more important. There are also some cases where the system has linear characteristics within the original input range, and nonlinear characteristics appear when the input range changes. When measuring fluid flow with a standard throttling device, for example, if a flow less than the specified Reynolds number is required, the throttling device’s outflow coefficient is not constant. As a result, there is a nonlinear relationship between the flow rate and the square root of the differential pressure across the throttling device. Besides, there are many ways to compensate for the nonlinear characteristics. One method is to make the compensated input and output relationship show a linear relationship; the other is to determine the output according to the nonlinear characteristics.

The compensation method of the nonlinear scale is to recognize the nonlinear relationship of input and output and use the nonlinear scale to reflect its nonlinear relationship. Early analog instruments often used this nonlinear compensation method. For example, for the temperature display of different graduation numbers and ranges, the scale of the display instrument is a nonlinear scale that satisfies the nonlinear characteristic. Similarly, the scale of the recording paper is also nonlinear. When measuring resistance with a nondigital multimeter, use an inverse nonlinear scale, etc. This nonlinear compensation method can only be applied to detection systems.

2.3. The Realization of Nonlinear Compensation. The method of realizing nonlinear compensation in hardware often adopts a multisegment polyline approximation. In the control system, a split-range control system can be used to send the output of the controller to the control valve in sections. Some valve positioners provide a multisegment broken line approximation algorithm, and some decentralized control systems also provide a quantization function module for the input signal, which is used for nonlinear compensation of the input signal. These methods are all methods of approximating nonlinear characteristics with multisegment polylines. The more segments are divided, the higher the degree of approximation. For example, the distributed control system can generally provide 16 to 20

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{nonlinear_properties.png}
\caption{Types of nonlinear properties.}
\end{figure}
segments of broken line approximation, which improves the accuracy of nonlinear compensation. The method of multisegment polynomial approximation uses interpolation to calculate the output of each segment interpolation point, and there will be jumps at the segment points. Therefore, the inverse function compensation method that uses a continuous equation to describe the nonlinear relationship has higher accuracy and can avoid the occurrence of the jump, etc. The inverse function of compensation method can be calculated using

\[ G_2c_2(\theta_{2i} - \theta_{2o}) = G_1c_1(\theta_{1o} - \theta_{1i}) \]  

(10)

The use of the neural network to achieve nonlinear characteristics is a commonly used method in recent years. The principle is that any nonlinear characteristic can be realized by a three-layer neural network. However, when the DCS or PLC is implemented, the calculation engineering is more complicated, including the settings of weights and biases. Therefore, it has not been widely used. At present, more simulation studies are being conducted.

\[ ab = (a_1 + \cdots + a_n)(b_1 + \cdots + b_n) = \sum_{i=1}^{n} a_i b_j \]  

(11)

The inverse function of the nonlinear characteristic function is connected in series with the link of the nonlinear characteristic, which can realize the compensation of the nonlinear characteristic. This is the most common method used in software implementation. With the application of microprocessors, the nonlinear characteristics of a large number of industrial production processes have been described by mathematical models, and their inverse functions can be directly determined or determined by some methods of curve fitting, such as nonlinear least squares method implementation. In addition to the multisegment polynomial approximation, the commonly used software implementation methods include Taylor series and polynomials. In recent years, NURBS spline functions have been used for approximation. Because it can be easily implemented in PLC or DCS, it is widely used in other fields and also receiving attention, which can be defined in

\[ R^2(y, \bar{y}) = 1 - \frac{\sum_{i=0}^{n}(y_i - \bar{y}_i)^2}{\sum_{i=0}^{n}(y_i - \bar{y})^2}. \]  

(12)

3. Tabu Search Algorithm and Its Optimization

The tabu search (TS) algorithm was first proposed by F. Glover in the late 1970s as a global step-by-step optimization algorithm [19]. It avoids local extreme points by extending the neighborhood search according to the knowledge obtained in the search process. The tabu search algorithm is a deterministic local minima jump strategy. The most important idea is to mark some objects that correspond to the previously searched local optimal solutions and try to avoid these objects in subsequent iterative searches (but not absolutely, mainly based on whether the contempt criterion is met). As a result, the tabu search algorithm possesses properties that other traditional optimization methods do not. Tabu search algorithm includes the following seven basic parameters: tabu object, tabu length, neighborhood function, evaluation function, contempt criterion, termination criterion, and memory frequency information.

3.1. Features of Tabu Search Algorithm. The tabu search algorithm is a global iterative optimization algorithm with strong local search ability. Compared with the ordinary optimization search algorithm, it adopts many unique methods and technologies. In the search process, poor solutions can be accepted, so it has a strong “climbing” ability. Then, it can be obtained by using

\[ \min F_{obj} = \min P_{loss} + \lambda \sum_{\beta} \left[ \frac{V_i - V_{lim}}{V_i_{max} - V_i_{min}} \right]^2. \]  

(13)

The new solution is not randomly generated in the neighborhood of the current solution but is better than the current optimal solution, or the optimal solution that is not tabu. Therefore, the probability of selecting an excellent solution is much greater than other solutions. It is suitable for solving multivariable, nonlinear, discontinuous, and multiconstrained global optimization problems and shows unique advantages.

3.2. The Operation Steps of the Tabu Search Algorithm. For many practical problems in engineering, the only reliable way to find the optimal solution is the exhaustive method, which searches the entire parametric space of the problem. However, the size of the variable search space in many engineering problems can be astronomical, and the tabu search can accept inferior solutions in the search process based on the memory function. Furthermore, defiance criteria can cause a jump out of the local optimal solution and into different regions of the solution space. Optimize the calculation to increase the likelihood of obtaining a better global optimal solution, and then, find the optimal solution in the global scope. The specific steps of the tabu search algorithm are shown in Figure 2.

3.3. Improvement of Neighborhood Search Strategy. The tabu search algorithm can be used to solve the problem of where to install the energy storage device and how to increase its capacity. The entire procedure can be thought of as a combinatorial optimization problem. The traditional field search can help to pinpoint the installation location. It is an operation of 1 and -1, so the entire process is understandable. When searching for the energy storage unit capacity neighborhood, the final obtained neighborhood is used as the installation position, and certain step size is used as the standard. It is simple to obtain a local optimal solution, but it does not guarantee the results. The solution is the most optimal solution on a global scale.

In this study, the area search neighborhood is appropriately improved according to the actual needs, to achieve the research purpose. To further improve the search efficiency of the traditional algorithm, the configuration capacity is set to
a fixed value to search the neighborhood. In this study, the corresponding nominal capacity of the selected energy storage device is determined as the neighborhood. At the same time, the number and capacity of the energy storage device must be within the constraints as given in

\[
\begin{align*}
V_{\text{min}} \leq V_i & \leq V_{i\text{, max}}, \quad i \in N_{PV}, \\
T_{k \text{ min}} \leq T_k & \leq T_{k \text{ max}}, \quad k \in N_T, \\
Q_{c \text{ min}} \leq Q_{c_i} & \leq Q_{c \text{ max}}, \quad i \in N_C, \\
V_i \text{ min} \leq V_i & \leq V_{i \text{ max}}, \quad i \in N_{PQ}, \\
P_{G_{i \text{ min}}} \leq P_{G_i} & \leq P_{G_{i \text{ max}}}, \quad i \in \{N_{PV}, S\}.
\end{align*}
\]  

(14)

The installation position of the energy storage device is fixed, its installation location is changed, and the search strategy is selected as the adjacent upstream and downstream nodes to carry out neighborhood search. While the installation capacity search strategy is chosen as different nominal capacities, the capacity of the energy storage device and the installation location change together. As a result, the adjacent upstream and downstream nodes are chosen as the installation location search strategy, and the neighborhood search is initiated.

The three neighborhood search algorithms mentioned above are addressed in this work. It is discovered that there is no search relationship between them, allowing the number of iterations to be regulated. It also has a better search range than the old technique, allowing it to avoid slipping into the local optimal solution. When the neighborhood search of the installation location is performed, the upstream and downstream nodes are the search targets, expanding to the entire planet. The energy storage unit’s installation position, for example, the upstream node and the downstream node,
and the adaption value function is determined for each node. The array contains the nominal value of various energy storage units, which clarifies the tabu search algorithm’s search range. It is evident where to position the energy storage device, and its energy storage capacity is acquired by optimizing the tabu search method.

4. Experimental Result Analysis and Simulation

The algorithm described in this paper was implemented and tested on a set of standard circuits to fix the issues of L-way segmentation and assessment, in which L is the number of levels. The change of vibration displacement and ideal vibration displacement of the hydraulic press in 4 working scenarios within 24 hours is analyzed to verify the compensation ability of the nonlinear compensation method.

Figure 3 shows the specific comparison results, which proves the method’s effectiveness of compensation capacity.

The amount of compensation will be reduced when the load equipment is not clear when it is in or out. The voltage amplitude of 8 nodes is higher than that of all the equipment in the above working state. It is not difficult to find that the hydraulic device is connected to 2 and 7 nodes, compared with when the energy storage device is not connected, the compensation displacement amplitude obtained after vibration loss increases significantly, and the degree of increase is significantly greater than the values that take nodes 1, 3 and 4, 5 as the access positions. It fundamentally solves the problem of the minimum value of compensation after vibration loss. If the system is connected to nodes 6 and 8, which are connected to the end nodes, the access compensation device can play an important role in regulating the surrounding pressure distribution.

During the entire system operation cycle, the compensation of node 8, the displacement increases significantly, but the displacement variation within 24 hours is significantly larger than that of nodes 2 and 7, so to achieve the expected effect, the access position of the compensation system should be nodes 2 and 7, indicating that the access position of the compensation determines the system performance. For the improvement of the situation, choosing a good location can play a role in stabilizing the running state of industrial equipment.

Table 1 lists the economic cost, access quota power capacity, and access location of the ESS corresponding to the above scenarios. Positions 2 and 7 are considered to be in a working state of full compensation strength and connection to the energy storage equipment in the three situations.

![Figure 3: Vibration offset of different hydraulic machines over time.](image)

| Number | G1 (million) | G2 (million) | G3 (million) | Connected point | Consume (KW) |
|--------|--------------|--------------|--------------|-----------------|--------------|
| 1      | 12.1         | 1.0          | 13.0         | 2-7             | 23           |
| 2      | 14.0         | 1.3          | 23.4         | 1-3             | 28           |
| 3      | 11.9         | 1.1          | 13.0         | 4-5             | 24           |
| 4      | 12.5         | 2.2          | 18.3         | 6-8             | 25           |

Table 1: Comparison among calculation results in each scenario of the actual industrial.
where some industrial equipment is removed. We obtained the expenditure shown in Table 1, while the cost table is shown in Figure 4. When the energy storage device is connected, the positioning system node vibration displacement and compensation displacement division are measured under full load conditions. The power consumption time to adjust for adequate displacement loss cannot be predicted in any of the four situations, according to the data in Table 1.

**Table 2: Nonlinear vibration and compensation of hydraulic press.**

| Vibration amount (mm) | 40  | 43  | 40  | 38  | 36  | 35  | 30  | 29  | 27  | 25  | 20  | 15  |
|-----------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| 70                    | 1.2 | 1.156 | 1.156 | 1.156 | 1.157 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.158 | 1.159 |
| 65                    | 1.5 | 1.156 | 1.156 | 1.156 | 1.157 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.158 | 1.159 |
| 66                    | 1.5 | 1.155 | 1.156 | 1.156 | 1.156 | 1.157 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.159 |
| 64                    | 1.2 | 1.155 | 1.156 | 1.156 | 1.156 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.158 | 1.159 |
| 62                    | 1.3 | 1.155 | 1.156 | 1.156 | 1.156 | 1.157 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.159 |
| 60                    | 1.1 | 1.155 | 1.155 | 1.156 | 1.156 | 1.157 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.159 |
| 58                    | 1.2 | 1.155 | 1.155 | 1.156 | 1.156 | 1.157 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.158 |
| 56                    | 1.5 | 1.155 | 1.155 | 1.156 | 1.156 | 1.157 | 1.157 | 1.157 | 1.158 | 1.158 | 1.158 | 1.158 |
When it is under full load operation, 2 and 7 are when all industrial equipment is running after the energy storage device is connected. The location with the lowest economic cost is the lowest cost for the equipment to compensate for sufficient displacement difference, the cost of line loss is also the lowest, and the total system cost is the lowest. Therefore, the location should be properly selected when connecting to the ESS; otherwise, the expected economic benefits cannot be achieved.

Figure 5 depicts the three scenarios of 1, 2, 3, and 4, where nodes 2 and 7 are connected to the energy storage device. At this time, the vibration displacement deviation of each node in the system is the same when compared to the original energy storage access location.

The mathematical model of hydraulic press vibration loss and compensation can be described by

$$\theta_{\text{loss}} = \frac{\theta_2 - \theta_1}{G_1c_1/UAm + 1/2(1 + G_1c_1/G_2c_2)} + \theta_u. \quad (15)$$

In Figure 4, the mathematical model of Equation (15) is drawn as a characteristic curve. It can be seen from this figure that if the flow characteristic of the control valve adopts the equal percentage flow characteristic, the nonlinearity of the controlled object can be roughly compensated. This depicts the relationship between the relative flow of the heating medium and the gain. As a result, equal percentage flow characteristics are frequently used in temperature control systems. This example demonstrates how the system exhibits nonlinear characteristics as the input signal range expands. When the heat transfer area in a process is increased, the temperature difference between the intake and outlet increases as well. As a result, the controlled item can run in the linear zone as well, removing nonlinearity.

The difference between the heat coefficient values in Table 2 is not significant, but due to the huge vibration amount and compensation value, the influence on the overall damage measurement is still significant. Therefore, piecewise linearization with the thermal coefficient can improve the measurement precision. The thermal coefficient value is stored in the memory of the heat meter. According to the consumption loss or compensation flow and the energy density at the corresponding pressure temperature, the instantaneous heat can be calculated, multiplied by the sampling time, and accumulated to obtain the total heat. The above calculation method is a nonlinear compensation method of local linear processing. Most European heat meters are calculated by the thermal coefficient method, but there are certain limitations in use in China, such as vibration loss and energy loss caused by inconsistent compensation.

5. Conclusions

The research of this paper fills the blank of the research of nonlinear vibration compensation methods in the field of forging hydraulic press. It not only expands the scope of nonlinear vibration compensation in forging hydraulic presses but also of nonlinear output regulation theory study and application. The research work of this paper will lay a foundation for the research of nonlinear output regulation in the field of forging hydraulic press. In the past, nonlinear characteristics are usually not desired. Therefore, when studying the system, try to hope that the linear relationship is necessary, because the linear system has many advantages, and the processing will be very convenient. With the advancement of precise control requirements and the advent of digital processing, software-defined hardware, and other technologies, the majority of actual processes are nonlinear. Even though research on nonlinear features has progressed significantly, the industry has accepted some compensation for nonlinear characteristics as a method. With the advancement of mathematical model correctness, software for nonlinear compensation (including dynamic nonlinear compensation) will have a bright future, deserving of attention and research in industry application and promotion.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflict of interest.

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