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ATTITUDE CONTROL OF AIR SPRING MOUNTING SYSTEM BASED ON FUZZY CONTROL

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ABSTRACT

Air spring is a kind of mount with excellent vibration isolation effect and it uses air as its elastic component. But its height is subject to constant change due to air leak or environment temperature and this restricts its engineering application. So some studies on attitude control are carried out, focusing on statically indeterminate and multivariable coupling air spring mounting systems in this paper. The Statically indeterminate problem is transformed through adding the constraint of loading evenness among air springs. After analyzing the model of this controlled object, a new control strategy based on coupling characteristic recognition is presented and combined with fuzzy logic control to realize attitude control of the multivariable coupling system. Finally, a test is conducted to show that the control strategy is feasible and the control system has good static and dynamic properties.

KEYWORDS

Statically indeterminate , multivariable coupling , air spring, attitude, coupling characteristic recognition, fuzzy logic control

1. INTRODUCTION

In engineering practice, some isolated equipments demand that the error between isolator's height and rated height should be controlled in a limited range [1]. Otherwise, normal operation of equipments will be affected. Air spring uses air as its elastic component. So air leak or change of environment temperature may change its height. It is very difficult to make an accurate mathematical model of air spring mounting system because it is a statically indeterminate and multivariable coupling system. The highly accurate attitude control is always one of the difficulties in air spring applications.

By far, there is little study on this control problem. The representative examples are reference [2] and [3]. In reference [2], an approximate mathematical model of a mounting system composed of one air spring is derived. By use of 0 type and 1 type control systems, the air spring height is controlled with the change of the isolated equipment weight. In reference [3], simulation and partial tests of a semi-active air spring suspension are done to a quarter-suspension and half-suspension model. Their studies have some limitations. So, attitude control of air spring mounting system has some significance.

In this paper, attitude control is implemented based on the characteristics of air spring mounting system. Some studies on transformation of statically indeterminate problem and control of multivariable coupling problem based on coupling characteristic recognition is carried out. Combined with fuzzy logic control, these studies are applied in this attitude control problem. A test is conducted in an air spring mounting system for a 200KW marine diesel generator set.

2. CHARACTERISTICS OF AIR SPRING MOUNTING SYSTEM

Consider a mounting system composed of *n* air springs (*n* is even) number $1, 2, \ldots n$. When all the air springs are at rated height, attitude of this system can be called aclinic.

Figure 1 shows the schematics of an air spring mounting system. The origin of the 2-dimension plane coordinate system lies coincident with the projection of the C.G. of the equipment to the installation plane of mounts. All the air springs are symmetric about the X axis.

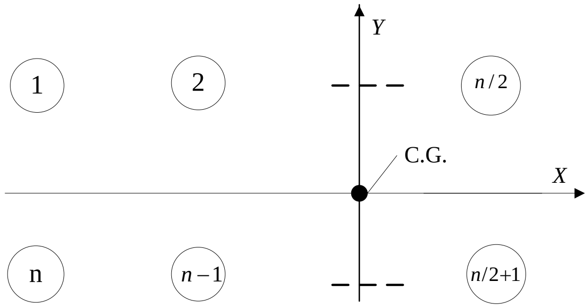

Figure1 Schematics of an air spring mounting system

The loading of each air spring T_i can be expressed as

$$T_i = P_i S_i \tag{1}$$

where P_i is the pressure of air spring and S_i is the effective area of air spring. If the height of air spring is fixed, S_i is constant and T_i is proportional to P_i.

To the mounting system in figure 1, if all the air springs have same heights, three static equilibrium equations can be written as

$$\begin{cases} \sum_{i=1}^{n} P_i = G/S_i \\ \sum_{i=1}^{n} P_i x_i = 0 \\ \sum_{i=1}^{n} P_i y_i = 0 \end{cases} \tag{2}$$

where n is the number of air springs, G is the gravity of the equipment, x_i, y_i are the co-ordinates of each air spring in the 2 dimensional plane coordinate system.

When $n \geq 4$, the solution of P_i is not determinate and the mounting system is a statically indeterminate system. There are coupling between height and pressure among all the air springs. The coupling intensifies as the number of air springs increases.

3. STUDY ON CONTROL METHODS

3.1. Transformation of the statically indeterminate problem

At present, the usual methods dealing with statically indeterminate problems are to find more constraints through the knowledge of material mechanics or structural mechanics by supplying static equations [4] [5].

In this paper, in view of life-span and security of air spring, additional constraint of the evenness of loading among all air springs is used to search an optimized pressure distribution as one of the charge /discharge decision-making rules. Then the statically indeterminate problem can be transformed and the mounting system will operate stably at this common pressure distribution over a long term.

Take Eq.1 as the equation constraints and import the optimization problem of the evenness of loading which is

$$\min \varphi(P) = \frac{1}{n}\sum_{i=1}^{n}\left(P_i - \frac{G}{S \cdot n}\right)^2 \tag{3}$$

where S is the effective area at rated height, $P = (P_1, P_2 \ldots P_n)^T$ is the pressure distribution, $\varphi(P)$ is the object function of optimization.

Solution of the above optimization problem gives the pressure distribution P^* under which the evenness of loading is best achieved.

3.2. Analysis of the model of this controlled object

The controlled object of this paper is a classic nonlinear MIMO system.

The input variables are charging time of each solenoid valve controlling the corresponding air spring. The output variables are the height of each air spring. The derivation of the system transfer function is difficult.

There is no coupling between input variables. So the MIMO system can be transformed into SIMO system directly which has only one input variable. This transformation can simplify largely the control problem with coupling in output variables.

The height and pressure of each air spring are synthetically considered to determine which air spring should be the input object.

3.3. Control strategy based on coupling characteristic recognition

There are many solutions to multivariable systems, such as decoupling control of linear (or nonlinear) multivariable systems [6] and stochastic multivariable systems [7]. All these solutions transform multivariable systems into many decoupling single variable systems by establishing mathematical model. It is difficult to apply these analytical methods to the complicated multivariable systems, such as air spring mounting systems.

In order to realize the attitude control of the SIMO system with coupling in output variables, a new control strategy based on coupling characteristic recognition is presented. The core of this strategy is to turn decoupling control into coupling characteristic recognition control.

The error of air spring height can be expressed as

$$\Delta h = h - H \tag{4}$$

where h is current height, H is rated height.

Assume Δh can be departed into two parts as follows

$$\Delta h = \Delta h_c + \Delta h_s \tag{5}$$

where Δh_c is the error of height due to the coupling of height between all the air springs, Δh_s is the error of height due to the change of gas mol amount or environment temperature.

The real intention of charge/discharge is to eliminate Δh_s. As Δh_s decreases, Δh_c will disappear due to the coupling of height.

The control strategy based on coupling characteristic recognition is to make a qualitative analysis of Δh_s in Δh through P_i of an air spring at same Δh. And the control input is given by the proportion of Δh_s.

A set of language information can be used to express this control strategy as, "Let Δh is constant, if P_i is bigger, then the proportion of Δh_s is smaller and the needed input is smaller. On the contrary, the proportion of Δh_s is bigger and the needed input is bigger."

Zadeh, the founder of fuzzy logic theory, once brought out the famous "Law of Incompatibility" [8], *i.e.*, "As complexity rises, precision statements lose meaning and meaningful statements lose precision." It is obvious that the processing of language information is an important approach in dealing with the control problem of complex system.

3.4. Control method

Air spring mounting system is a complex statically indeterminate and multivariable coupling system with time-delay property. So it is very difficult to establish a mathematical model to determine the relationship between charge/discharge time and attitude change. In order to realize attitude control, the control system should have intergrated capability of data and language information processing. It's obvious that the traditional control methods are incompetent.

Fuzzy logic control technology, which is one of the modern intelligent control technologies, is applied to realizing the attitude control. The fuzzy controller is essentially a nonlinear system, so it has good approach capability to controlled objects [9]. It can organically combine data and language information in fuzzy rules and realize many control assignments which is incompetent for traditional control methods. The control method based on recognition of coupling in section 3.3 is adopted in the design of fuzzy controller.

4. DESIGN OF THE FUZZY CONTROLLER

Figure 2 shows the structure of a two-inputs and one-output fuzzy controller which has 2 common fuzzy controllers.

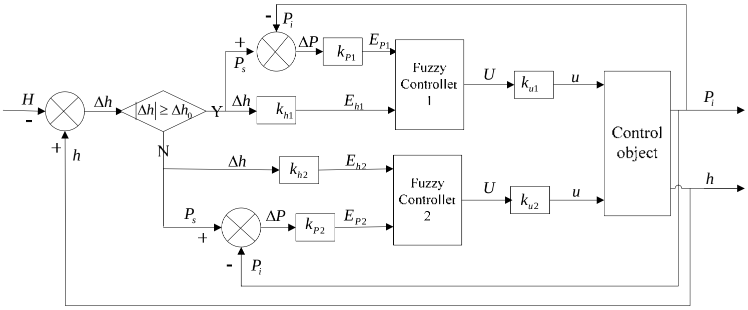

Figure2. Schematics of the fuzzy controller

Δh and ΔP are the input variables of the fuzzy controller. P_s is the pressure of gas source (P_s is viewed 0 in discharge program). ΔP is the error between P_s and

P_i which can be written as $\Delta P = P_s - P_i$. u is the output variable, *i.e.*, charging or discharging time of the solenoid valve. k_{h1}, k_{P1}, k_{h2}, k_{P2}, k_{u1}, k_{u2} is respectively the scaling coefficient of fuzzy controller 1 and 2. Δh_0 is the switch threshold value of the two fuzzy controllers.

Design of this fuzzy controller is aiming at convenient engineering applications. Meanwhile, this fuzzy controller can provide a big output to enhance the dynamical property of this control system when Δh is big. On the contrary, it will provide a small output to ensure the static precision and avoid overload, even oscillation.

We introduce *ITAE* to select appropriate Δh_0 based on abound testing data. *ITAE* can make an integrated estimate of the dynamic and static capability of the control system and it can be written as

$$J(IATE) = \sum_{i=1}^{m} i \cdot \left| \Delta \bar{h} \right| \cdot T^2 \tag{7}$$

where i is sampling sequence number, T is sampling interval, $\Delta \bar{h}$ is the mean error of heights of all mounts. The Δh_0, which makes the $J(IATE)$ minimum, is the best threshold value.

In this paper, ΔP is a very important input variable. The control strategy based on coupling characteristics recognition and the different gas flow properties at different pressure of air spring can be integrated in the design of fuzzy rules after ΔP is introduced.

Based on the theory of gas flow, the flowing speed is ultrasonic when $P_s \geq 1.893 P_i$ and then the gas flow is very big. Otherwise, the flowing speed is subsonic and then the gas flow will decrease quickly with the increase of air spring pressure. In order to ensure a high static precision of Δh, P_s shouldn't be very big because the gas flow through solenoid valve may not be small enough. The property of subsonic gas flow is needed to be used to enhance static precision at the end of control process.

Fuzzy field of Δh, ΔP, u is respectively ｛-5，5｝，｛-4，4｝，｛0，5｝. Δh and ΔP has seven fuzzy subsets, *i.e.*, NL, NM, NS, ZERO, PS, PM, PL. u has five fuzzy subsets, *i.e.*, ZERO, PS, PM, PL, PG. All the input and output variables adopt triangular membership function. Table 1 shows the fuzzy rules in this paper.

Table1. Fuzzy rules of U

U		Eh						
		NL	NM	NS	ZERO	PS	PM	PL
Ep	NL	ZERO				PS	PS	PS
	NM					PS	PS	PM
	NS					PS	PM	PM
	ZERO	PG	PL	PM	ZERO	ZERO		
	PS	PL	PL	PL	PM			
	PM	PM	PL	PM	PS			
	PL	PS	PM	PS	PS			

Eh is the fuzzy number corresponding to Δh, Ep is the fuzzy number corresponding to ΔP, U is a fuzzy output of the fuzzy controller.

The Mamdani fuzzy algorithm is used in this fuzzy controller. And it adopts Max-min composition, minimum implication and center average defuzzifier.

5. TEST EXAMPLE

In this paper, the test installation is an air spring mounting system for a 200KW marine diesel generator set. Figure 3 shows its basic structure.

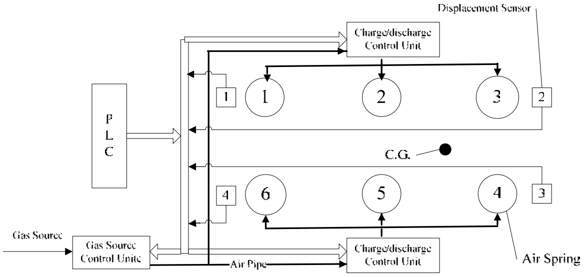

Figure3. Schematics of a test example

The main component of this control system includes one Siemens S7-200 PLC, four displacement sensors (the redundant one is used to check the measure results), two charge /discharge control units, one gas source control unit. Each charge/discharge control unit comprises three 2/2 way solenoid valves and three pressure sensors. The gas source control unit comprises a 2/3 way solenoid valve and a pressure sensor. The 2/3 way solenoid valve is used to discharge air spring.

The mounting system consists of six air springs. The rated height of each air spring is 95mm. They are symmetrically installed in the base where four rigid mounts are installed.

Both G and C.G. are unknown at initial phase. But we can suppose that the pressure of each air spring corresponding to the optimal evenness of loading is equal. For instance, the pressure can be the maximal pressure at which the air spring can be loaded. Operate the control system and the real optimal pressure distribution will be worked out till the attitude of this mounting system is aclinic for the first time.

The control system works out that equipment weight is about 3.2T and the real optimal pressure distribution is

$$P^* = (0.43, 0.59, 0.74, 0.74, 0.59, 0.43)^T MP_a$$

After initial operation, scaling coefficients can be determined as $k_{h1} = 1.1$, $k_{P1} = 3$, $k_{u1} = 150$; $k_{h2} = 1.9$, $k_{P2} = 10$, $k_{u2} = 15$. The appropriate Δh_0 is 2.0mm after introducing *ITAE*.

This section mainly introduces the test results of six unpressured air springs to reflect the properties of control system extensively. The gas source pressure is adjusted to 0.9～1.0Mpa in this test. Figure 4 shows the changing process of displacement data of the four sensors from unpressured state to aclinic attitude state.

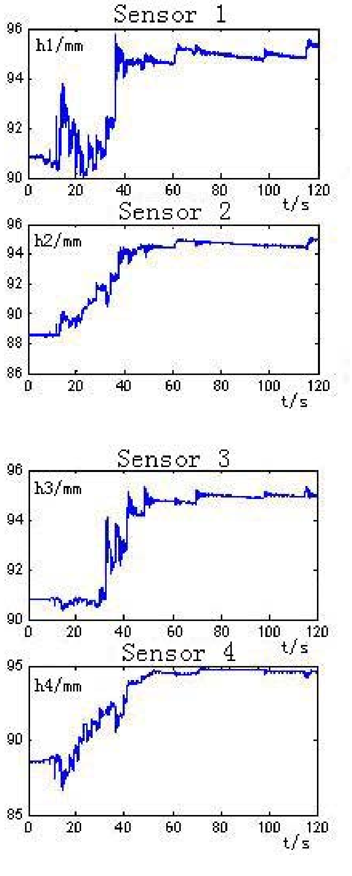

Figure4. Measure data of the four displacement sensors

The measure results of the sensors have been transformed into the heights of #1, #3, #4 and #6 air springs.

From the whole control process, it can be seen that the height of each air spring gradually approximate and converge to the rated height. The whole attitude control process lasts for 60s. The final static precision achieves ±0.3mm.

Though charge is going on from 0s to 15s, there is no change of height of each air spring because the reacting force offered by the air springs is not big enough to make the generator set leave the rigid mounts. #3air spring first leave the rigid mount at about 17s and then the other air springs leave. The strategy of fast charge is used in this term and it may shorten the needed time of the whole control process.

From the test data, it can be seen that the increase of height of a certain air spring will have an uncertain effect on the others. This indicates the difficulty in establishing the system mathematical model.

The height of #1 air spring increases to 96mm at 38s and restores to 95.1mm by itself after several seconds. This indicates that the coupling has a great effect on the height of air spring. So combined the control method based on coupling characteristic recognition with the design of fuzzy controller is very important to the attitude control.

When the attitude control is accomplished, the pressure of each air spring is

$$P = (0.44, 0.59, 0.73, 0.75, 0.6, 0.44)^T MP_a$$

This pressure distribution is very close to the above optimization result. This shows that the control system can realize the evenness of loading.

When slight air leak happens, the needed time of attitude control is less than 2s and the static precision is un-variable.

6. CONCLUSIONS

In this paper, the statically indeterminate problem is transformed into a statically determinate one through adding the constraint of loading evenness . After analyzing the model of the controlled object, a new control strategy based on coupling characteristic recognition is carried out to deal with the control problem of multivariable coupling. This control strategy is combined with the design of fuzzy controller to realize the attitude control of an air spring mounting system. The test results show that this control strategy is feasible and the designed fuzzy controller promises the control system has good static and dynamic properties. This control system has potential in engineering application. Applying air spring mounting systems to marine propulsion engines and do some further studies on attitude control will be the latter work.

NOMENCLATURE

T_i	air spring loading
P_i	air spring pressure
S_i	effective area of air spring
G	gravity of equipment
x_i, y_i	mount co-ordinates
H	air spring rated height
S	effective area at rated height
P	pressure distribution vector of air springs
$\varphi(P)$	object function of optimization
P^*	pressure distribution vector opposite to the best evenness of loading
h	air spring height
Δh	error of air spring height
Δh_c	error of height due to coupling of height
Δh_s	error of height due to change of gas's mole amount or environmental temperature
P_s	gas source pressure
ΔP	error between P_s and P_i
U	output of fuzzy controller
u	output variable *i.e.* open time of electromagnetic valve
k_{h1}, k_{h2}	scaling coefficient of Δh
k_{P1}, k_{P2}	scaling coefficient of ΔP
k_{u1}, k_{u2}	scaling coefficient of U
NL	negative large, fuzzy linguistic variable
NM	negative medium, fuzzy linguistic variable
NS	negative small, fuzzy linguistic variable
PS	positive small, fuzzy linguistic variable
PM	positive medium, fuzzy linguistic variable
PL	positive large, fuzzy linguistic variable
PG	positive great, fuzzy linguistic variable

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