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Nonlinear Dynamics Analysis of Vibratory Subsoiler

[1]Li Li-Xin and [2]Ji Hui-Liang
[1]College of Engineering, Shenyang Agricultural University, Liaoning, Shenyang, 110866, China
[2]School of Automobile and Trafic, Shenyang Ligong University, Liaoning, Shenyang, 110159, China

Abstract: Acting force between deep-shovel and soil is complicated variable in farming. To establish nonlinear mechanics model of vibratory subsoiler, force analysis of deep-shovel is carried out, and the soil is equivalent to a viscoelastic material. It adopts qualitative method to analyze the effect of small disturbance on system bifurcation. Runge-Kutta numerical integration algorithm with variable time step was used to solve the system equation, and phase plane plots and bifurcation diagrams of system are obtained. On the basis of the above data, the influence of exciting force on nonlinear dynamics of system is analyzed. The results indicate that motion of deep-shovel is relatively complicated under the special working condition, and the system movement which is frequently changeful from period n to chaos present singularity phenomenon. A vibratory subsoiler is tested in site, and the analysis further shows that chaos can be used to reduce traction resistance of tractor by contrast with simulation data and experimental data.

Key words: Vibratory subsoiler, nonlinear dynamics, chaos, bifurcation

INTRODUCTION

In agricultural engineering, scholars at home and abroad adopt linear theory and experiments to investigate vibratory subsoiler system (Li *et al*., 2012; Wu *et al*., 2010; Dong *et al*., 2010; Shahgoli *et al*., 2010; Sahay *et al*., 2009; Sakai *et al*., 1993; Slattery and Desbiolles, 2002). Gebregziabher and etc., studied tillage components adopting finite. Shmulevich and etc., simulated the interaction between the soil and tillage components adopting discrete element method and performed force analysis for tillage components with different shapes (Shmulevich *et al*., 2007; Shmulevich, 2010). In vibrating tillage, the subsoiler carries out soil cutting and lifting and carries out reciprocating motion. When the subsoiler is in cutting motion, the plow pan breaks up, the friction among soil particles and friction element method (Gebregziabher *et al*., 2007) between the soil and the subsoiler will change; when the subsoiler lifts up the soil, part of the throwing soil falls down, collides with the subsoiler and disrupts the soil furthermore. Because the complex and varied acting force between the soil and the subsoiler, vibratory subsoiler system has strong nonlinear characteristics.

During vibrating loosening, the vibro-impact between the subsoiler and the soil, vibration friction's impact on the nonlinear dynamic characteristics of vibrating subsoiler system and effects of deep tillage can not be neglected. Adopting qualitative method and Runge-Kutta method, this article concerns the theoretical solution and numerical simulation of the vibratoty subsoiler system, studied the exciting force's impact on nonlinear dynamics characteristics, conducted a vibration drag-reduction experiment using vibratory subsoiler and investigated chaos's impact on the tractive resistance of a tractor furthermore.

NONLINEAR DYNAMIC MODEL OF VIBRATORY SUBSOILER AND THE ANALYTIC SOLUTION OF THE BIFURATION

Nonlinear dynamic model of vibratory subsoiler: Simplified model of vibratory subsoiler system is shown in Fig. 1. The model will think soil as a viscoelastic material with a spring and a damper instead of soil, the "y" direction vibration load is applied at the end of deep loosening shovel.

System dynamics differential equation in "y" direction is:

$$M\ddot{y} + c\dot{y} + ky + F_M(\ddot{y}, \dot{y}, y) = me\omega^2 \sin \omega t \quad (1)$$

where, M is the deep-shovel mass, *c* is the equivalent damping of soil, k is soil the equivalent stiffness, $F_M(\ddot{y}, \dot{y}, y)$ is soil reaction, E (t) is exciting force which is applied at the end of deep-shovel, E (t) = $me\omega^2 \sin \omega t$, *y* is displacement of deep-shovel.

Section soil reaction equation is shown below:

Corresponding Author: Li Li-Xin, College of Engineering, Shenyang Agricultural University, Liaoning, Shenyang110866, China

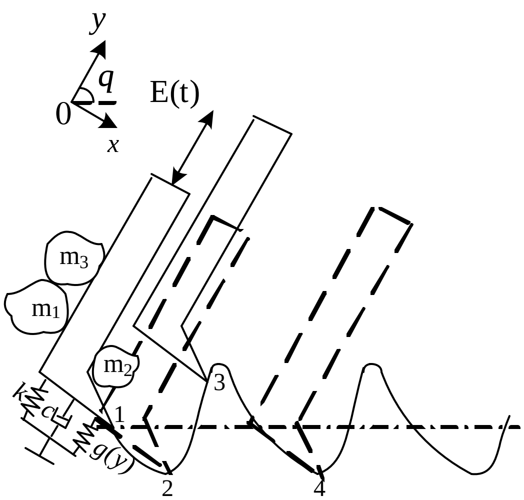

Fig. 1: Simplified model of vibratiory subsoiler system

$$F_M(\ddot{y},\dot{y},y)=\begin{cases} f(m_1 g\cos\theta+m_1\ddot{y}c\tan\theta) \\ +fm_2 g\cos\theta+g(y), \quad \phi_{Lk}\langle\phi\langle\phi_{Lm} \\ m_3\ddot{y}\sin\theta, \\ \phi_{Lm}-2\pi\langle\phi\langle\phi_{Hk,}\phi_{Hm}-2\pi\langle\phi\langle\phi_{Lk,} \\ f(m_3 g\cos\theta+m_3\ddot{y}c\tan\theta)+g(y), \\ \qquad \phi_{Hk}\langle\phi\langle\phi_{Hm} \end{cases} \tag{2}$$

where, the "f" is soil friction coefficient of deep loosening shovel, g (y) is elasticity restoring force of soil, θ is the grave Angle, φ_{LK} is initial Angle of sliding soil in cutting process,φ_{Lm} is the Angle of soil sliding in the process of cutting, φ_{HK} is soil initial Angle of sliding in the process of ascension, φ_{Hm} is the Angle of soil sliding in the process of ascension.

The elasticity restoring force model is:

$$g(y)=\begin{cases} \eta\left(y-\sum\Delta y_{i-1}\right)^3+B_1 & \dot{y}>0 \\ \eta\left(y+\sum\Delta y_{i-1}\right)^3-B_1 & \dot{y}<0 \end{cases} \tag{3}$$

where, i is the time number of cycling load, Δy_{t-1} is the displacement difference after unloading period hysteresis for each time, Σ is sum, η and B_1 are constant, of which η is index of hysteresis.

The analytic solution of the bifurcation of vibratory subsoiler: This article studies the impact of the bifurcation on vibratory subsoiler system bifurcation with main resonance according to the relation of universal unfolding and unfolding parameters:

$$\frac{k}{M}=\omega^2+\sigma, \tau=\varepsilon t$$

σ is tuning parameter.

Adopt small parameter ε and can result in:

$$\ddot{y}+\frac{k}{M}y=\varepsilon\begin{pmatrix} -\frac{c}{M}\dot{y}-\sigma y-\frac{1}{M}F_M(\ddot{y},\dot{y},y) \\ +\frac{me\omega^2}{M}\sin\omega t \end{pmatrix} \tag{4}$$

Suppose the solution of Eq. 4 to be y = α cos φ, φ = ωt+θ, obtain similar solution with average-linkage method:

$$\begin{cases} \frac{da}{d\tau}=-\frac{1}{a}\left[\frac{ca\omega}{2M}-0.0127a^3+\frac{me\omega^2}{2}\sin\theta\right] \\ \frac{d\theta}{d\tau}=-\frac{1}{\omega\tau}\left[-\frac{1}{2}\sigma a-1.64a^3+\frac{me\omega^2}{2}\cos\theta\right] \end{cases} \tag{5}$$

Take:

$$\frac{da}{d\tau}=0, \frac{d\vartheta}{d\tau}=0, \lambda_1=0.0926\left(me\omega^2\right)^2,$$
$$a_1=0.0926\left[\left(\frac{c\omega}{M}\right)^2+\sigma^2\right], a_2=-\frac{c\omega}{M}+129\sigma$$

Bifurcation equation is obtained:

$$\alpha^6-\lambda_1+\alpha_1\alpha^2+\alpha_2\alpha^4=0 \tag{6}$$

Transformation:

$$\alpha^2=x-\frac{\alpha_2}{4}$$

Eq 6 is transformed to:

$$x^3-\lambda+\varepsilon_1 x+\varepsilon_2 x^2=0 \tag{7}$$

There:

$$\lambda=\lambda_1+\frac{1}{4}\alpha_2-\frac{3}{64}\alpha_2^3, \varepsilon_1=\alpha_1-\frac{7}{16}\alpha_2^2, \varepsilon_2=\frac{1}{4}\alpha_2^2$$

Bifurcation set is B = Φ.

Hysteretic set is:

$$H=\left\{\varepsilon_1=\frac{1}{3}\varepsilon_2^2\right\}$$

Hysteretic set is points on the non-durable bifurcation diagram of universal unfolding, indicating the qualitative behaviour of bifurcation diagram of universal unfolding will alter, when the bifurcation equation is slightly disturbed.

SIMULATION OF VIBRATORY SUBSOILER SYSTEM

Take:

$$u = My,\ \tau' = \omega_0 t,\ \nu = \frac{\omega}{\omega_0},\ \omega_0 = \sqrt{\frac{k}{M}}$$

Equation 1 is dimensionless to be:

$$\ddot{u} + \mu\dot{u} + \alpha u + \beta F_M(\ddot{u}, \dot{u}, u) = kk \sin \nu\tau' \tag{8}$$

$$F_M(\ddot{u}, \dot{u}, u) = \begin{cases} F_{11} + F_{12}\ddot{u} + \gamma\left(u - \text{sgn}(\dot{u})\sum \Delta u_{i-1}\right)^3 \\ + \text{sgn}(\dot{u})B_1, \quad \phi_{Lk} \langle \phi \langle \phi_{Lm} \\ F_{21}\ddot{u}, \quad \phi_{Lm} - 2\pi \langle \phi \langle \phi_{Hk}, \phi_{Hm} - 2\pi \langle \phi \langle \phi_{Lk}, \\ F_{31} + F_{32}\ddot{u} + \gamma\left(u - \text{sgn}(\dot{u})\sum \Delta u_{i-1}\right)^3 \\ + \text{sgn}(\dot{u})B_1, \quad \phi_{Hk} \langle \phi \langle \phi_{Hm} \end{cases} \tag{9}$$

where,

$$\mu = \frac{c}{M\omega_0},\ \alpha = \frac{k}{M\omega_0^2},\ \beta = \frac{1}{\omega_0^2}, kk = me\nu^2,$$

$$\gamma = \frac{\eta}{M^3}, F_{11} = fg\cos\theta(m_1 + m_2)$$

Exciting force's impact on periodic motion of the System: This study uses the fourth order Rounge-Kutta method on the system for the numerical simulation study. The basic parameters of vibratory subsoiler system as follows: $\mu = 0.034$, $\alpha = 0.41$, $\beta = 0.0002$, kk = 0.1~0.6, p = 2, $\gamma = 0.000044$, $F_{11} = 0.335$, $F_{12} = 0.271$, $F_{21} = 0.4$, $F_{31} = 0.15$, $F_{32} = 0.176$.

Selecting the exciting force as the bifurcation parameter, the range of the exciting force is 0.15, 0.26, 0.34, 0.42 and 0.55, the system phase diagram with different the exciting force is as shown in Fig. 2.

Iinfluence of exciting force on system bifurcation: When $\mu = 0.034$, $\alpha = 0.41$, perform numerical simulation taking the exciting force as the bifurcation parameter and the range is 0.1~0.6 and generate a bifurcation diagram of displacement and exciting force as shown in Fig. 3.

TEST AND ANALYSIS

Test mainly use Dong Fang Hong tractor, vibratory subsoiler, dynamometric system, vibration test system, dynamic strain gauge and soil hardness instrument.

The dynamometric system includes II dynamometric frame and three octagonal ring sensors (Chen *et al.*, 2007;

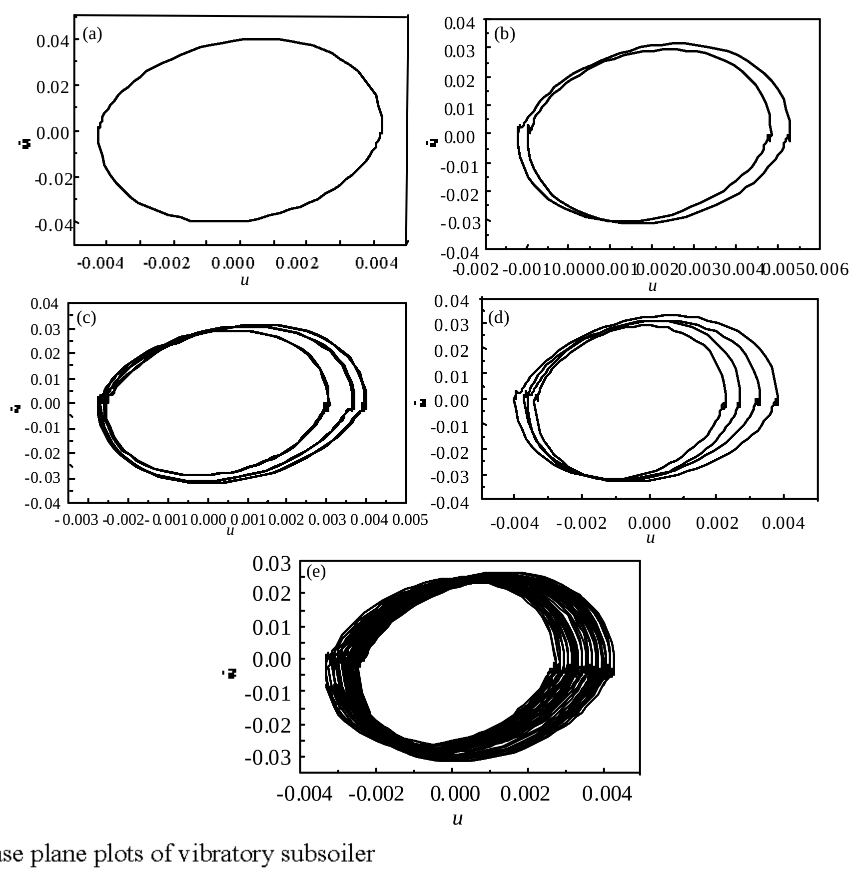

Fig. 2: Phase plane plots of vibratory subsoiler

Table 1: Data of exciting force and tractive resistance

Conditions	Exciting force/N	Tractive resistance/kN
1	60.389	2.82
2	60.88	2.79
3	70.358	2.27
4	70.778	2.56
5	80.175	2.47
6	80.716	2.34
7	90.17	2.22
8	90.66	2.21
9	10.34	2.17
10	10.56	2.02

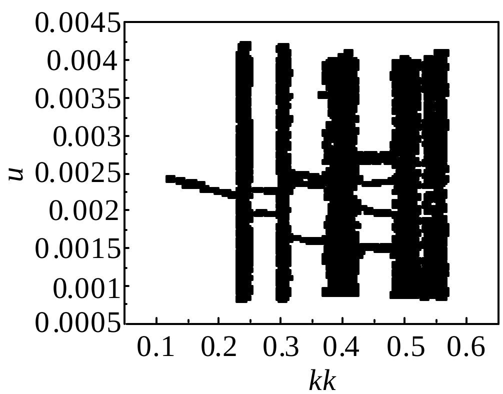

Fig. 3: Bifurcation diagram of system

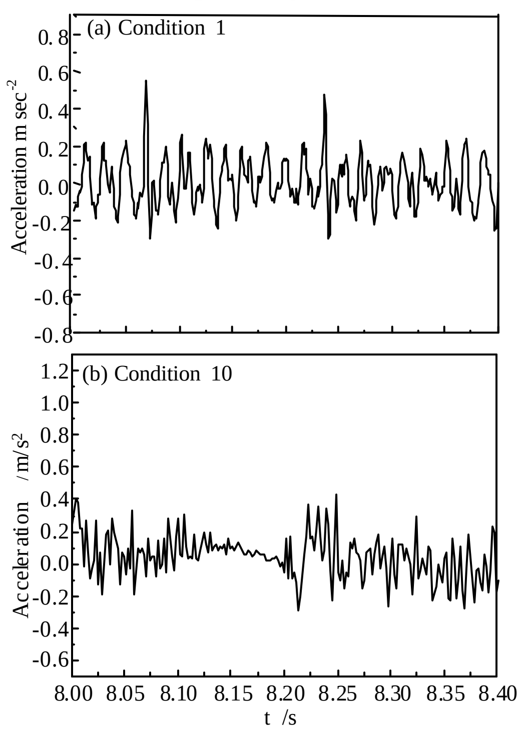

Fig. 5: Acceleration response curves

O'Dogherty, 1996). II dynamometric frame can be adjusted from top to bottom, left to right, this can ensure that when the dynamometric system connects three-point linkages of tractor, its upper and lower rod links are paralleled with the ground, so that the accuracy of the dynamometric data is guaranteed.

Data of exciting force and tractive resistance is shown in Table 1.

Acceleration response curves are shown in Fig. 5 under condition 1 and condition 10.

DATA ANALYSIS

Seen from Fig. 2, when the exciting force increases, the change process of period of oscillation is from T to. 2T, 3T, 2^2T, ..., 2^nT; when kk = 0.15, the system carries out period 1 motion; when kk = 0.26, the system carries out period 2 motion; when kk = 0.4, the system carries out period 3 motion; when kk = 0.5, the system carries out period 4 motion; when kk = 0.55, the system carries out chaotic motion. Because of impacts of friction inside the soil, elastic restoring force, sliding and rolling friction between the soil and the subsoiler and inertia force of the throwing soil, the motion behavior of the system is relatively complex

As seen from Fig. 3, according to the difference of exciting force parameters, periodic motion of the system enters into chaos from non-smooth bifurcation and the displacement response tends to be period1-chaos-period 2-chaos-period 4-chaos. When kk = 0.25, the system enters into period 2 motion from chaos; when kk = 0.33, the system enters into period 3 motion from chaos; when kk = 0.43, the system enters into period 4 motion from chaos; when kk = 0.48, the system enters into chaos again from period 4 motion.

From data in Table 1, when the exciting force is relatively small, the tractor's tractive resistance is relatively big. As seen from Fig. 5, when the exciting force is relatively big, the system's motion is chaotic. This conclusion is consistent with the above-mentioned analysis, indicating that utilizing chaos properly can reduce tractive resistance.

CONCLUSION

This article establishes a nonlinear dynamic model considering the single-degree-of-freedom system of acting force of soil, conducted a analysis combing the thoery and numerical simulation and found out that when the exicting force is of particular value, the system exists bifurcation and its motion shifts to chaos from periodic motion.

The theoretical analysis and the experiment shows that the exciting force's impact on nonlinear dynamics characteristics is complex. When the exciting force in a particular range and the value is small, the chaotic interval is relatively narrow; when the value is big, the chaotic interval is relatively wide. Using chaos properly can reduce the tractor's tractive resistance and improve the effect of deep tillage.

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