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Aeroelastic Response Of A Three Degree Of Freedom Wing-Aileron System With Structural Non-Linearity

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Abstract

This paper investigates the aeroelastic response of a wing-aileron system subject to incompressible flow. A three degree of freedom wing-aileron model is derived and free-play non-linearity is introduced in the aileron control circuit stiffness. The resulting equations of motion for the system are integrated numerically to give the time history of the wing-aileron motion. It is found that the aileron demonstrates a sustained oscillation well below the linear flutter speed. The effects of the amount of free-play on the aeroelastic response of the system is examined. The amplitude of the sustained oscillation is strongly dependent on the amount of free-play in the aileron stiffness and could provide a catastrophic feedback accelerating the wear which leads to the free-play.

Introduction

In determining the flutter characteristics and the aeroelastic responses of aircraft structures the assumption of structural linearity has usually been made. However, aircraft structures often exhibit non-linearities such as free-play, that have significant effects on the flutter speed and aeroelastic responses. The flutter phenomena is a self-excited vibration, wherein the structural system absorbs energy from the air stream. If the structure moves at speeds higher than the flutter speed it will demonstrate divergent oscillation which may result in a catastrophic failure.

It is known that systems with structural non-linearity also illustrate two different types of aeroelastic responses below the flutter boundary. The first mode is called Limit Cycle Oscillation (LCO), where the structure demonstrates sustained oscillation. The second aeroelastic response which is observed in non-linear structures is chaotic vibration. Non-linear systems experiencing chaotic vibration and LCO are likely to fail due to fatigue and aging. It is also known that aging has significant effect on developing concentrated non-linearity in mechanical systems, one particular example is worn control surface hinges that lead to free-play non-linearity.

In recent years, the modelling and analysis of aerosurfaces with structural non-linearities have been the subject of numerous investigations. The effects of non-linear structural terms on the aeroelastic response and the flutter of aircraft structures have been performed by several investigators. The first study of non-linear aeroelastic problems of an aircraft wing was conducted by Woolston et al.[1] They investigated the effects of several types of non-linearities in the stiffness. They developed an analysis by analog computer to study the effects of structural non-linearities. McIntosh et al.[2] performed wind tunnel test of a two-degrees of freedom model with non-linear stiffness.

Yang and Zhao [3] performed experimental and theoretical analysis to investigate oscillations of a two-dimensional wing model with non-linear pitching stiffness. They made a comprehensive study of LCO of the two degree of freedom model subjected to incompressible flow using the Theodorsen function. Zhao and Yang [4] also analysed two dimensional airfoils with cubic pitching stiffness in incompressible flow to investigate the chaotic behaviour of the self excited dynamic system.

Price et al [5] studied a two dimensional airfoil with a free-play non-linearity in pitch subjected to incompressible flow. They evaluated the aerodynamic forces using Wagner's function and the resulting equations integrated numerically to give the time response of the airfoil motion. They detected regions of LCO for velocities below the linear flutter boundary. Price et al [6] also studied a two dimensional airfoil with cubic structural non-linearity in pitch by numerical methods. Kim, and Lee [7] analysed a two-dimensional flexible airfoil with a free-play non-linearity in pitch in the subsonic flow range.

A two dimensional model with concentrated non-linearities has been chosen to perform aeroelastic analysis by most of investigators, because of its simplicity and usefulness. However, one aircraft structure which is very susceptible to the development of structural non-linearity, such as free-play, due to aging is the control surface hinges. In this paper, a three-degree of freedom wing aileron section with free-play non-linearity in control surface restoring torque characteristics and subject to incompressible flow has been studied. The work is part of a research program studying the effects of aging on control surface flutter [8].

A Two Degree of Freedom System

The system studied by several investigators is the basic two degree of freedom airfoil shown in Figure 1. Effects of several types of non-linearities, such as free-play, and cubic stiffness for an airfoil with plunge and pitch degree of freedom have been considered. Previous studies usually considered structural non-linearities in pitch.

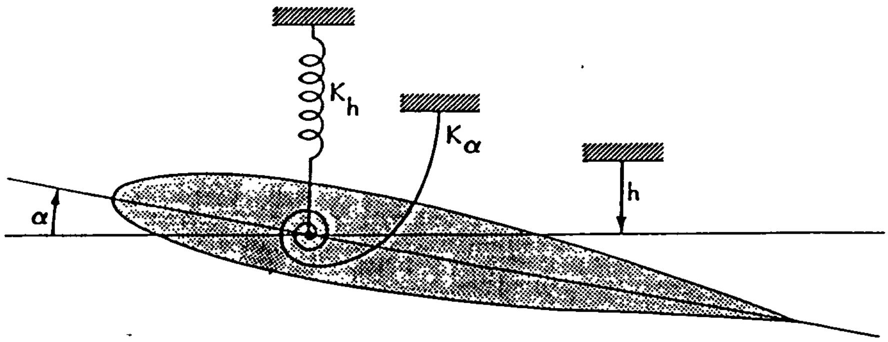


Figure 1. Two degree of freedom airfoil.

The equations of motion of the system are written as

$$m\ddot{h} + S_\alpha \ddot{\alpha} + k_h h = Q_h, \qquad S_\alpha \ddot{h} + I_\alpha \ddot{\alpha} + M(\alpha) = Q_\alpha. \qquad (1)$$

where h is the plunging displacement, α is the pitching angle, Q_h and Q_α are the aerodynamic loads, and $M(\alpha)$ represents the non-linear structural restoring moment in the pitch direction.

The oscillation response of the above system has been investigated by different analytical and experimental methods. The results show the existence of LCO and chaotic vibration behaviour below the flutter speed of the linear system. [1-7]

The Three Degree of Freedom System

As mentioned before, the aeroelastic response of a two DOF system with free-play stiffness non-linearity has been studied by several investigators. In order to study the aeroelastic response of a wing and control surface model with structural non-linearity, a three degree of freedom system as shown in Figure 2 is investigated. Structural non-linearity, in the form of free-play is present in the system.

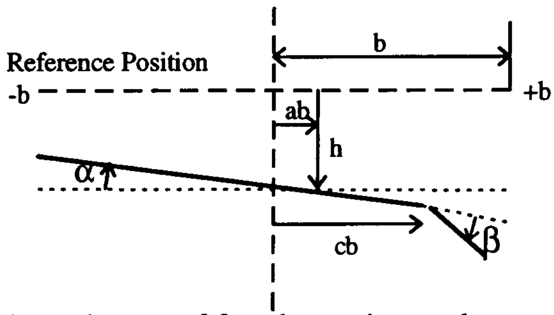


Figure 2. Three degree of freedom wing and control surface.

b = semichord

cb = distance between midchord and aileron hinge, positive if aft of midchord

ab = distance between midchord and elastic axis, positive if aft of midchord.

The governing equations of motion are

$$M\ddot{h} + S_\alpha\ddot{\alpha} + S_\beta\ddot{\beta} + k_h h = Q_h$$
$$S_\alpha\ddot{h} + I_\alpha\ddot{\alpha} + \left[(c-a)bS_\beta + I_\beta\right]\ddot{\beta} + k_\alpha\alpha = Q_\alpha \qquad (2)$$
$$S_\beta\ddot{h} + \left[(c-a)bS_\beta + I_\beta\right]\ddot{\alpha} + I_\beta\ddot{\beta} + M(\beta) = Q_\beta$$

where β is control surface displacement, M is mass of wing-aileron segment (per unit span), I_α is the mass moment of inertia of the wing-aileron segment about the elastic axis, S_α is the static mass moment of the wing-aileron segment about the elastic axis, I_β is the mass moment of inertia of the aileron about the aileron hinge line, and S_β is the static mass moment of the aileron about the aileron hinge line. The stiffness of bending and wing torsion are represented by k_h and k_α respectively. $M(\beta)$ is the non-linear restoring moment. In this paper free-play non-linearity in control surface stiffness is studied. The free-play non-linearity is described by

$$M(\beta) = \begin{cases} k_\beta(\beta - \beta_0) & \beta > \beta_0 \\ 0 & -\beta_0 > \beta > \beta_0 \\ k_\beta(\beta + \beta_0) & \beta < -\beta_0 \end{cases}$$

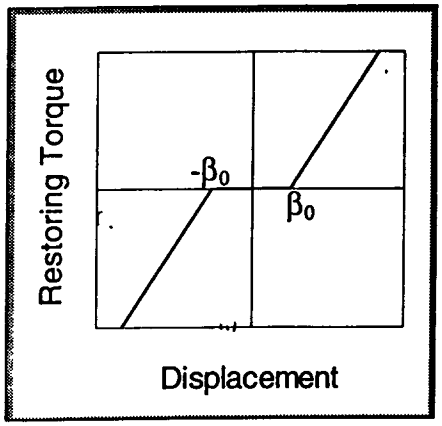


Figure 3. Free-play nonlinearity.

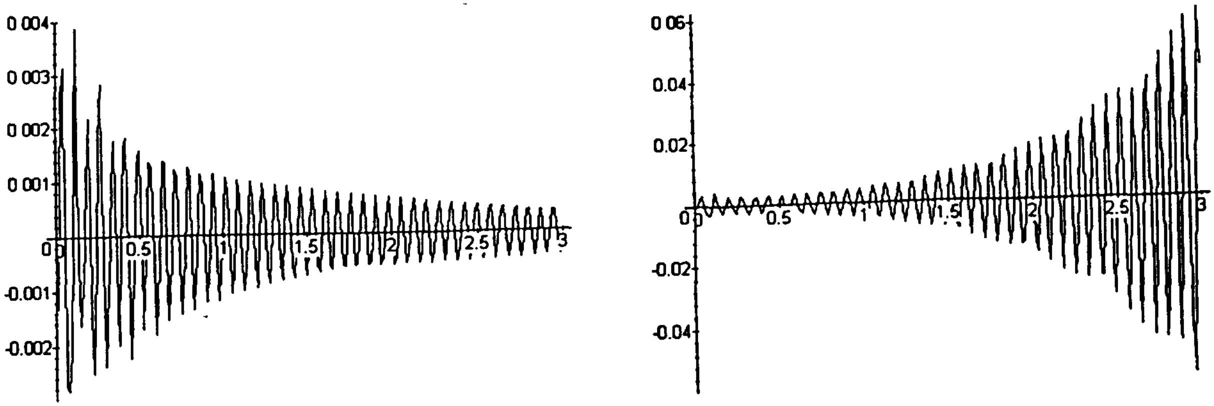
Q_h, Q_α, and Q_β are the incompressible aerodynamic loads. For incompressible flow the aerodynamic loads can be calculated in terms of the Theodorsen function.

Numerical methods have to be employed to find a time history response solution of Equation (2). In this paper a fourth order Runge-Kutta numerical integration routine is employed in the numerical simulation. The influence of the magnitude of structural non-linearity on the response of the system is investigated.

Simulation Results

In order to illustrate the response of the non-linear wing control surface system shown in Figure 2, a case with the following system parameters: m = 0.65 slugs, I_α = 3.375 slug-ft^2, I_β = 0.1 slug-ft^2, S_α = 0.456 slug-ft, S_β = 0, k_h = 1642 lb/ft, and k_α = 22517 lb-ft/rad has been studied. The chord length of the wing is 6.25 ft. The elastic axis is located at 35% chord and the control surface hinge line is located at 75% chord.

Prior to non-linear analysis, the linear flutter velocity, V_f, was obtained by removing the free-play and then increasing the air speed, U, in specific steps until divergent oscillation occurred. The linear flutter speed was found equal to 375 ft/sec. Figure 4 shows two typical time histories of control surface displacement for the linear system and 0.1 ft initial plunge disturbance. The linear system shows a damped decay response at 300 ft/sec, below V_f, and divergent response at 450 ft/sec, above the critical flutter speed.



(a) U = 300 ft/sec (b) U = 450 ft/sec

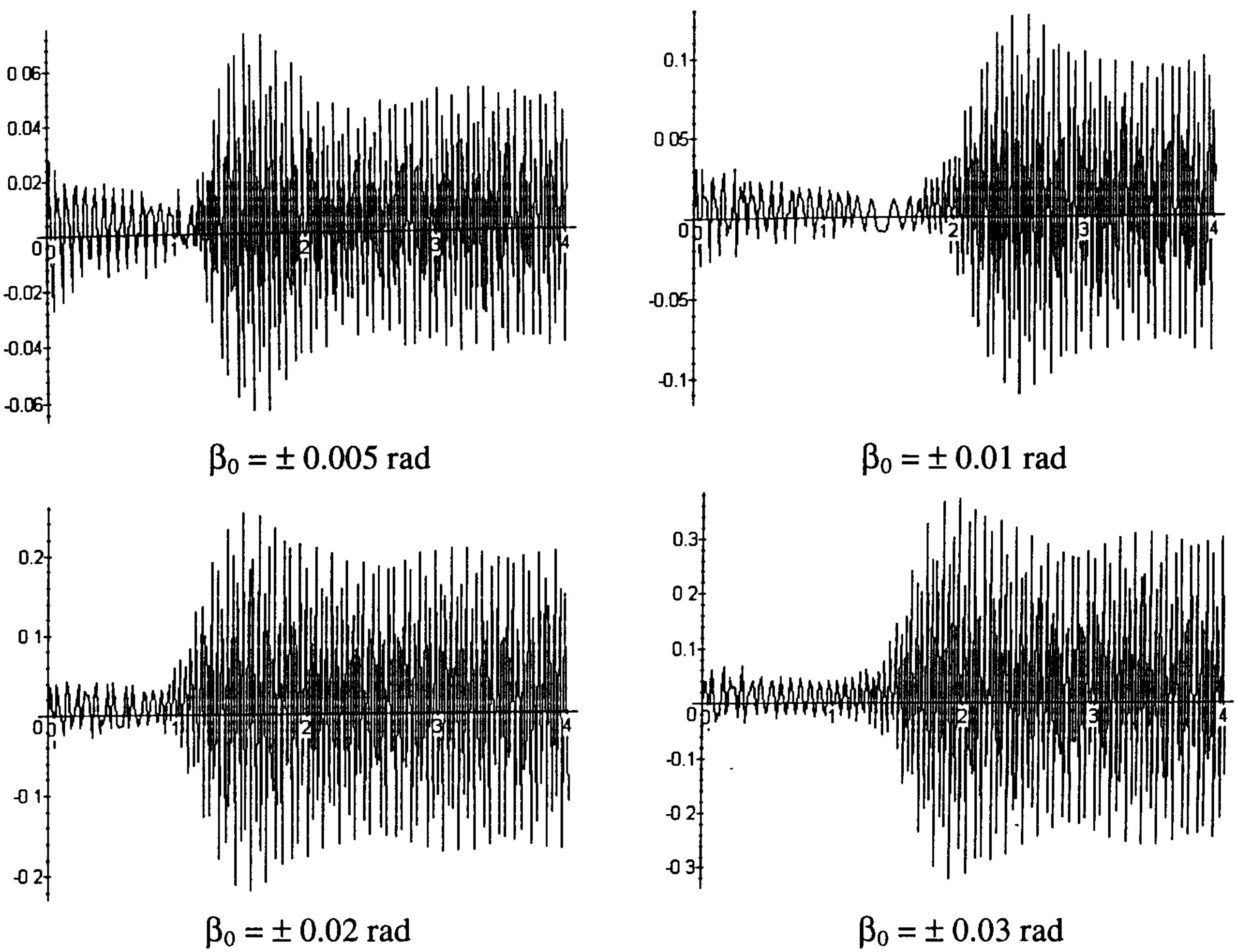
Figure 4. Time history response of the control surface displacement for linear system.

The non-linear system shows limit cycle oscillation at an air speed of 250 ft/sec. In order to study the sensitivity of the system response to the free-play band, non-linear analyses with four different β_0 were performed. Time histories for ±0.005 rad, ±0.01 rad, ±0.02 rad, and ±0.03 rad free-play in control surface displacement, and initial pitch rotation of 0.05 rad at this air speed are shown in Figure 5. The calculated time history responses show that as the free-play band, β_0, was increased for a fixed initial pitch disturbance, the magnitude of limit cycle oscillation increased. Figure 6 shows the relationship between the magnitude of control surface oscillation and the amount of free-play in control surface stiffness.

Proposed Experimental Set Up

It is known that wear in control surface hinges produces free-play in the control circuit. It is also shown in this research that the free-play in control surface stiffness produces limit cycle oscillations well below the linear flutter boundary which will result in the development of more free-play in the control circuit, due to wear and aging processes. Therefore it is proposed that the majority of this research should concentrate on the development of free-play in control surface hinges due to the LCO.

An experimental rig has been developed to study the development of free-play, as shown in Figure 7. The eye-end of a control surface actuator is chosen for the wear test. A shaker with a vibration controller is used to simulate the complicated load environment which occurs on an aircraft. The shaker is powered by a power amplifier and it is suitable to generate precisely controlled dynamic forces over a wide frequency range. Sinusoidal and random excitation forces are being applied by the shaker. The response is detected by an accelerometer attached on the shaker.



$\beta_0 = \pm\, 0.005$ rad

$\beta_0 = \pm\, 0.01$ rad

$\beta_0 = \pm\, 0.02$ rad

$\beta_0 = \pm\, 0.03$ rad

Figure 5. Time history response of the control surface displacement for non-linear system.

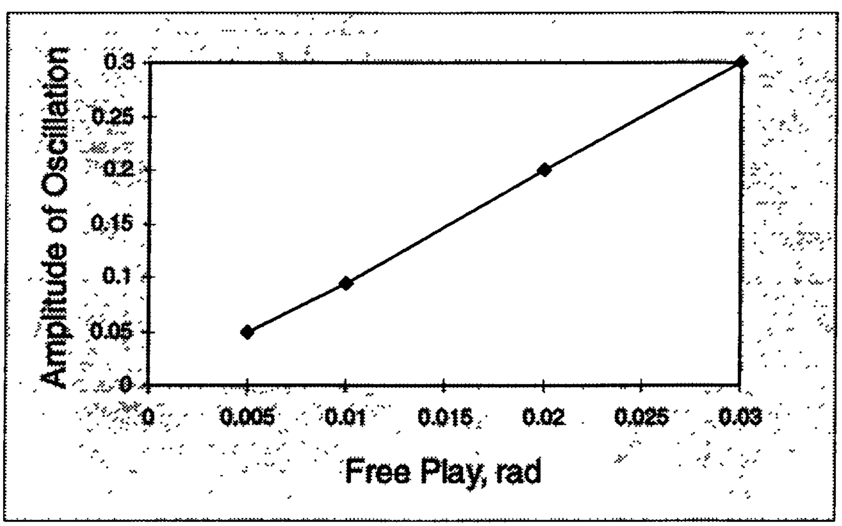


Figure 6. Effects of free-play nonlinearity on the control surface oscillation.

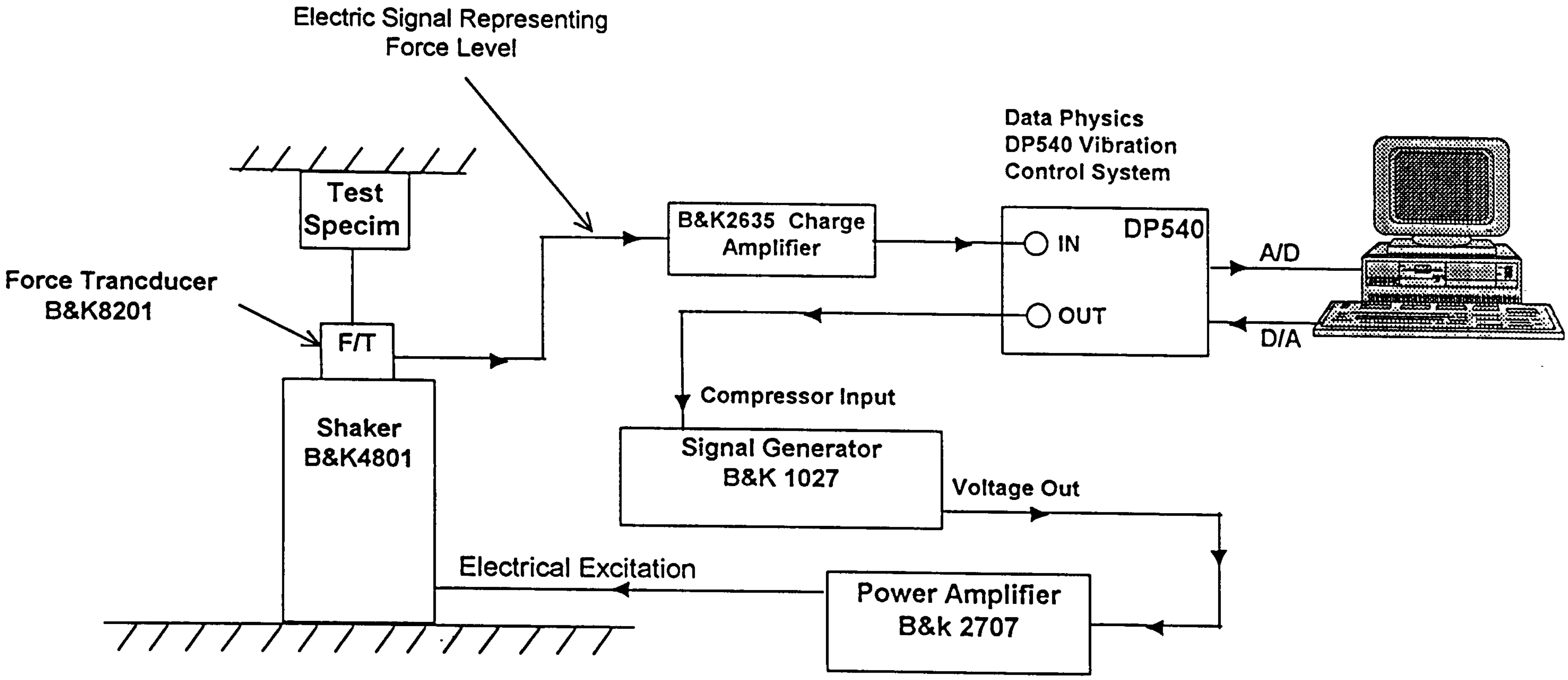


Figure 8. Proposed test rig.

Conclusion

A numerical method has been developed to simulate the aerodynamic response of a wing and control surface with structural non-linearity. Free-play nonlinearity has been considered in this paper. However, the technique can be applied to different structural non-linearity such as stiffness variations .

Results for a three degree of freedom wing-aileron model with structural free-play nonlinearity in control surface displacement illustrate sustain control surface oscillation for velocities well below the linear flutter boundary. The amplitude of the oscillation for a particular initial condition is strongly dependent on the amount of free-play.

In this work a number of cases with different system parameters have been analysed. Further work is required to investigate the effects of initial conditions on the behaviour of the system. Also, further work is being directed toward the experimental study of the development of free-play in the control surface stiffness due to sustained oscillations. The positive feed back from non-linear vibration to the development of free-play in the control circuit is being studied.

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