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AN INVESTIGATION OF MODE SHIFT FLUTTER SUPPRESSOR SCHEME FOR EMPENNAGES

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Abstract

In this paper, the scheme of mode shift flutter suppressor for empennages is investigated both theoretically and experimentally. The basic approach is to provide a tip balancing weight taking the form of an overhang flexible bar with an impact damping element. The theoretical calculation results show that the mechanism of this type of flutter suppression is due to the *shifting of critical flutter mode by the impact damper*. Test mode of this flutter suppression scheme is designed and tested in the wind tunnel, experimental results also exhibit the phenomenon of mode shift. The agreement between experimental and theoretical results comfirms the feasibility of the mode shift flutter suppressor scheme for empennages. By using this scheme, the flutter speed of an empennage model is increased by 29. 4%.

I . Introduction

Much effort has been expended for the purpose of determining and predicting the flutter characteristics of empennages[1]. When serious flutter problems (excessively low flutter speeds) are found to exist, however, the usual methods for alleviating the trouble have consisted of altering the empennage stiffness or shifing its center of gravity by a cut-and-try procedure which must be tailored to the peculiarities of the particular empennage. Thus, it is considered desirable to develop a general type of empennage flutter suppression scheme which can be quickly and reliably applied to an empennagc without requiring drastic alteration of the structure or addition of appreciable mass. For this consideration, some empennages have to provide balancing weight taking the form of an overhang bar installed on its tip. In this paper, a special device is investigated to further improve flutter condition of the above mentioned configuration. The measure lies in that, instead of the rigid bar, a *flexible bar is used combined with an impact damping element*. The pertinent parameters for this flutter suppressor are the flexibility of the overhang bar and the properties of the impact damper used.

First of all, in the present investigation, flutter calculation is carried out for the undamped empennage/bar system with varying tip bar flexibility which is represented conveniently by its eigen-frequency ω_β. Results of the flutter analysis are depicted in a so-called flutter boundary plot which is consist of two flutter mode branches. In the lower ω_β range, high ω_F branch is the critical one and the flutter mode keeps to be a bar-oscillating mode[2]. By employing impact damper the bar-oscillating flutter mode will be suppressed and flutter will occur in other critical mode until air speed reaches a higher value than the flutter speed for empennage with rigid balancing weight.

Doublet lattice method is used for unsteady aerodynamics and V-g method for flutter calculation. Both equivalent linearization and numerical integration methods are used in the nonlinear analysis with

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damping force. Experimental investigation is perfromed to verify the above theoretical analysis. A solid wooden wing is tested in low spseed wind tunnel. The model has trapezoidal plane form and has two degrees of freedom, namely, rolling and pitching about two perpendicular axes.

A tip mounnted bar-mass system is used to represent the analytical model of overhang balancing weight bar for simplicity and convenience to adjust parameters, e. g. by changing the lumped mass and the leaf spring. The experimental results agree well with the analytical results and the flutter speed of the damped empennage/bar system is increased by 29. 4% comparing with that of the undamped empennage/bar system, by which the feasibility of the mode shift flutter suppressor scheme is confirmed.

II. Theoretical Analysis

Mathmatical Model

The mathmatical model of the empennage with tip mounted bar-mass system is shown in Fig. 1. The system has three degrees of freedom, which are empennage rolling θ, pitching φ and bar pitching β. The equation of motion is

$$[M]\{\ddot{\xi}\}+[K]\{\xi\}=\{Q\} \tag{1}$$

where

$$[M]=\begin{bmatrix} I_\theta+m_\beta y_H^2 & -I_{\theta\varphi}-m_\beta X_H y_H & m_\beta y_H X_c \\ -I_{\theta\varphi}-m_\beta X_H y_H & I_\varphi+m_\beta X_H^2 & -m_\beta X_H X_c \\ m_\beta y_H X_c & -m_\beta X_H X_c & I_\beta \end{bmatrix} \tag{2}$$

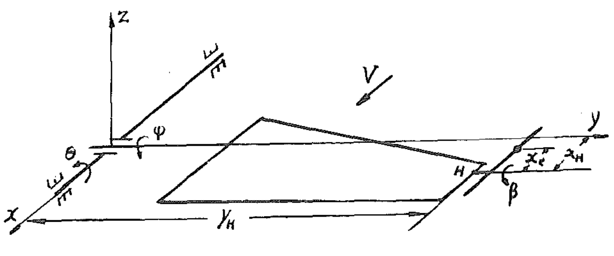

Fig. 1 Scheme of empennage/bar system

$$[K]=\text{diag}[k_\theta \quad k_\varphi \quad k_\beta] \tag{3}$$

$\{\xi\}=[\theta,\varphi,\beta]$ are the generalized coordinates.
I_θ, I_φ, $I_{\theta\varphi}$ are the generalized masses of empennage. m_β, I_β are the mass and mass moment of inertia of the bar-mass system respectively

$$\{Q\}=\begin{Bmatrix}\{Q_w\}\\ 0\end{Bmatrix}=q[A]\{\xi\} \tag{4}$$

where, $\{Q_w\}$ is the generalized aerodynamics of empennage, $[A]$ is the generalized aerodynamic influence coefficient matrix which is calculated by doublet lattice method, q is the dynamic pressure.

Equivalent linearization of Damping

For an impact system of two masses I_φ and I_β, the assumption of two impacts occurring in each one period has been justified by previous studies[3], then the energy dissipation is

$$\Delta E_1=(1-e^2)\frac{I_\varphi I_\beta}{I_\varphi+I_\beta}\dot{\beta}_-^2 \tag{5}$$

$\dot{\beta}_-$ is the relative speed before impact, e is the coefficient of restitution,
from the above assumption, there will be

$$\dot{\beta}_-^2=|\beta_0|^2\omega^2 \tag{6}$$

ω is the oscillating frequency, $|\beta_0|$ is the amplitude. The enery dissipated by a equivalent linear viscous damping is

$$\Delta E_2=\int_0^{2\pi/\omega} C_\beta\dot{\beta}^2 dt=\pi\omega C_\beta|\beta_0|^2 \tag{7}$$

from $\Delta E_1=\Delta E_2$, we obtain.

$$C_\beta=\frac{(1-e^2)}{\pi}\cdot\frac{I_\varphi I_\beta}{I_\varphi+I_\beta}\omega$$

with this damping, the equation of the damped system can be written as

$$[M]\{\ddot{\xi}\}+[C]\{\dot{\xi}\}+[K]\{\xi\}=[Q] \tag{8}$$

where

$$[C]=\mathrm{diag}[0\ 0\ C_\beta] \tag{9}$$

By solving equations (1) and (8) the flutter characteristics of the undamped and damped empennage/bar system can be obtained.

Numerical Simulation

The motion limiting property of impact damper can be simulated adequately by numerical integration. Equation (1) is converted into the state space, and has the form:

$$\{\dot{y}\}=[B]\{y\} \tag{10}$$

$\{y\}$ is the state vector, which includes the aerodynamic augmented arguments. The impact conditions should be simulated as:

when $|y(3)|=\bar{\beta}$ then

$$\begin{cases} y^+(6)=-ey^-(6) \\ y^+(5)=y^-(5)+(1+e)\cdot\dfrac{I_\beta y^-(6)}{I_\varphi+I_\beta} \\ y^+(3)=\bar{\beta} \qquad (y^-(3)>0 \\ y^+(3)=-\bar{\beta} \quad (y^-(3)<0) \end{cases}$$

"$-$", "$+$" indicate the time immediately before and after impact respectively, $\bar{\beta}$ is the clearance of impact damper. The flutter stability of the damped system can be determined from the response calculation.

Ⅲ. Experimental Investigation

Model and Its Mounting

The model has a bar-mass system flexibly mounted at its tip, the model can roll about θ-θ axis and pitch about φ-φ axis, the pitching and rolling stiffnesses are provided by leaf springs and they are adjustable to get different pitching/rolling frequency ratio, this model has strictly two degrees of freedom so that there will be no mode truncation error in the analysis. The bar-mass system is hinged to the wing and its pitching stiffness is also simulated by a leaf spring. To aviod the deformation caused by gravitation, the model system is vertically mounted in the wind tunnel, as shown in Fig. 2. The parameters of the test model are listed in Table 1.

Table 1 Parameters of test model

I_θ(kgm^2)	I_φ(kgm^2)	$I_{\theta\varphi}$(kgm^2)	m_β(kg)	I_β(kgm^2)	ω_θ(rad/s)
0.022	0.0068	0.00172	0.102	0.0015	12.41
ω_φ(rad/s)	x_H(m)	y_H(m)	x_c(m)	d/l	ω_β(rad/s)
30.614	0.09	0.45	0.05	0.1	15.708

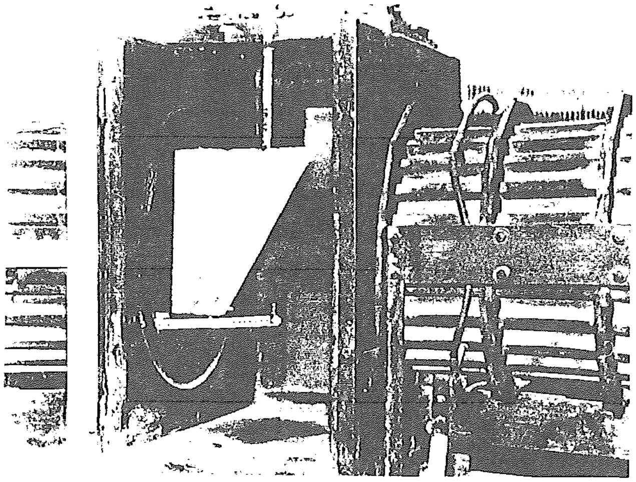

Fig. 2 Installation of the test model

Impact Damper

From a practical consideration, damping element applied to the bar-mass system should be compact and simply functioning, these requirements rule out usage of the conventional viscous damper and the impact damper is prefered. It is designed to be a fork with one end fixed on the empennage tip, another end overhung, and the bar is just located in the middle of the fork as shown in Fig. 3

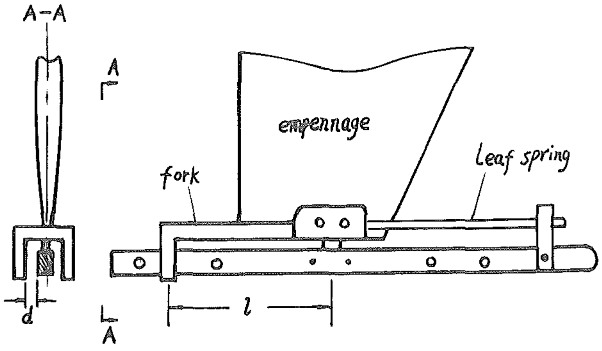

Fig. 3 Installation of impact damper

IV. Results and Discussion

Flutter calculation

The flutter boundary plot (V_F vs ω_β plot) of the empennage/bar system is calculated and shown in Fig. 4. It can be seen that the boundary is consist of two branches one with higher flutter frequency ω_F, another with lower ω_F. In the lower ω_β range, high ω_F branch is the critical one, where the flutter speed V_F incveases rapidly with ω_β. The flutter mode is bar-pitching dominated mode, when the critical ω_β^* is reached, the flutter speed V_F rises to a peak value and flutter mode transition occurs. Then the low flutter frequency branch emerges, becoming the flutter boundary, and the empennage surface vibration is dominant in the flutter mode. Afterwards V_F drops and decreases gradually to the asymptotic flutter speed corresponding to the rigid balancing weight case.

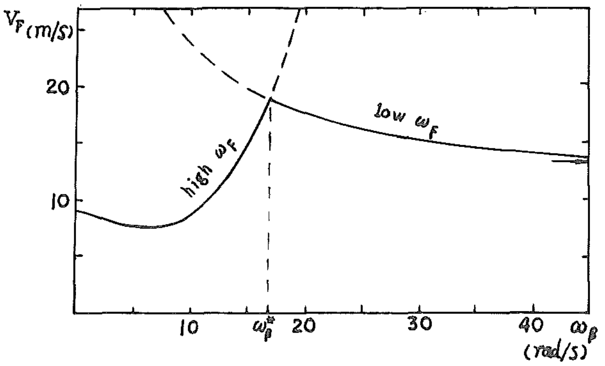

Fig. 4 Flutter boundary of empennage/bar system

When the equivalent damping coefficient C_β is introduced, for the tuned empennage/bar system ($\omega_\beta = 15.7$ rad/s) the flutter calculation results show that the flutter speed is raiscd from 16m/s to 20m/s, but the flutter mode has no significant change. The corresponding numerical simulation results show that, with impact damper, the flutter mode of the undamped empennage/bar system changes from bar pitching dominant to wing pitching dominant, because the bar pitching of the damped system is limited in a very small clearance.

From the above analysis, it can be seen that the effect of mode shift flutter suppression is just due to the use of impact damper for a flexible overhang bar-mass system. The mechanism of damping and motion limiting is the key to this suppression scheme.

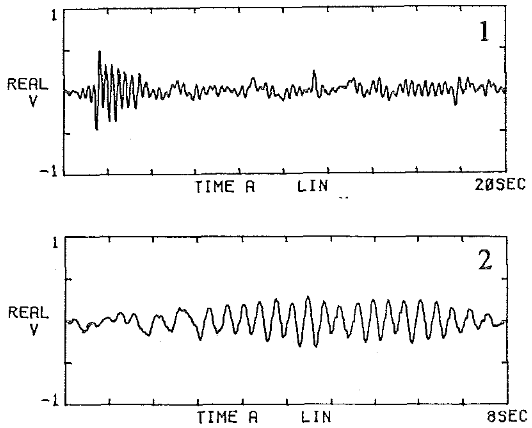

Fig. 5 (1)response of damped system of V=19m/s
(2) response of damped system at V=21m/s

Experiments

At first, the empennage with rigid bar is tested and the flutter speed is 14m/s, then the impact fork is turned down so as to let the bar pitching freely, the flutter speed is raised to 17m/s. Afterwards, the impact fork is turned up and the bar can only oscillate within the clearance of the the fork. When the air speed increases to 21m/s. The damped empennage/bar system is stable, Fig. 5 are the time histories of the system at V=19m/s and V=21m/s recorded by CF940. As air speed increases to 22m/s, the system stability losses and flutter occurs. The flutter speed is increased by 29.4% with the application of the so called mode shift flutter suppressor.

During the experiment, it is seen that the flutter quality of the damped empennage/bar system is also improved, that is, the flutter occurrence is changed from violent type to mild type.

Just as the results of numerical analysis, the test results show that the flutter mode of the undamped system is bar-pitching dominant, and the pitching of the bar is nearly out of phase with the empennage pitching, and the empennage pitching is rather small. When flutter occurs to the damped system, the flutter mode shifts to the coupled empennage rolling and pitching mode, the bar oscillation is limited within the clearance and looks like moving with the empennage as a whole.

V . Conclusion

1. The flutter suppression tests of the present work are satisfactory. The flutter speed of the damped system is increased by 29. 4% comparing with the undamped system. With which the feasibility of this method is verified.
2. The mode shift flutter suppressor scheme for empennages is an effective approach for flutter clearance, the mechanism of this technique is to use the damping and motion limiting characteristics of impact damper, combined with a tuned flexible overhang bar-mass system, shifting the lower flutter speed mode to a higher one.
3. The flutter suppression scheme proposed is convenient to apply in engineering flutter clearance design. Besides, it not only raises the flutter speed, but also improves the flutter quality of the system, the implementation of this scheme does not require drastic alteration of the structure.

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