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Effects of Fan, Ducting and Powerplant Characteristics on the Cushion Stability of Air Cushion Vehicles

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A theoretical study on the cushion stability of vertically oscillating air cushion vehicles, including the peripheral and the plenum chamber craft, is reported. In the analysis, the influences of fan, ducting and powerplant characteristics, which are frequently disregarded in existing analyses, are fully considered and general formulas which include both the peripheral and the plenum chamber craft are derived. It has been shown that the assumptions of constant momentum flux of the jet or constant total pressure at the nozzle exit during oscillations are not valid in general. The circumstances under which such assumptions are valid almost never occur, and the influences of fan, ducting and powerplant characteristics are very significant for both types of craft. It has also been shown that a positive damping force always acts on a statically stable plenum chamber craft. A numerical example suggests that, under certain circumstances, an abrupt change from the stable condition to the unstable condition might occur as a consequence of a small change of the fan characteristics.

Nomenclature

A	= function of x_i
a	= dimensionless coefficient
c	= peripheral length of nozzle for peripheral craft or peripheral length of effective base area for plenum craft
b	= dimensionless coefficient
C_d	= discharge coefficient
d	= diameter of fan
f	= dimensionless coefficient
G	= stability parameter, Eq. (34)
g	= dimensionless coefficient
h	= hoverheight
$\dot{h}$	= derivative of h with respect to time
J	= momentum flux of jet across unit peripheral length of nozzle exit
L_f	= shaft horsepower of fan
L_p	= shaft horsepower of engine
m_h, m_p	= mass flow coefficients
n_f	= rotational speed of fan
n_p	= rotational speed of engine
p_c	= cushion pressure
p_{ch}, $p_{c\dot{h}}$, $p_{c\phi}$	= stability derivatives
p_f	= total pressure just behind fan
p_j	= total pressure of jet at nozzle exit
Q_c	= amount of air fed into cushion in unit time
Q_f	= volume flow rate of fan
Q_j	= volume flow rate of jet leaving unit peripheral length of nozzle exit
S	= effective base area
S_f	= fan exit area
t	= nozzle thickness
V	= stroke volume of engine
x_i	= instantaneous value of a quantity
α, β, γ	= dimensionless coefficients
ζ	= duct loss coefficient
η_t,	= transmission efficiency
κ	= reduction ratio
λ_f	= shaft horsepower coefficient of fan
λ_p	= shaft horsepower coefficient of engine
ξ	= volume flow coefficient of fan
ρ	= density of air
ψ	= pressure coefficient of fan
ϕ	= parameter representing the position of throttle valve for reciprocating engine
$\phi_1, \phi_2, \ldots$	= parameters assigning the operation condition of powerplants

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Introduction

SINCE Tulin[1] presented a method for analyzing the cushion stability of oscillating air cushion vehicles, similar treatments have been made by many researchers such as Eames,[2] Payne,[3] Webster,[4] Lin[5] and Walker.[6] In most of these analyses, however, the variations of the operating conditions of the fan, ducting, and powerplant (e.g. engines) during the oscillation have been fully disregarded, and the arbitrary assumptions of constant momentum flux of the peripheral jets or constant total pressure at the nozzle exits have been made. Within the authors' knowledge, Walker's work[6] is the first example that considers the influences of fan and ducting characteristics. In his analysis, however, the characteristics of the powerplant are still disregarded. In Ref. 7, one of the authors analyzed the cushion stability of vertically oscillating air cushion vehicles of the peripheral jet scheme by fully considering all these influences and demonstrated that the situation under which the momentum flux or the total pressure remains constant during oscillation almost never occurs. In Ref. 7, the numerical results for a particular model of the peripheral jet air cushion vehicle are also compared with the results of the forced oscillation tests and it is shown that the theory gives reasonable results.

In what follows, the method developed for the peripheral craft in Ref. 7 is extended, and generalized formulas which include both the peripheral and the plenum chamber craft are obtained. The formulas presented for the peripheral craft in Ref. 7 will be easily derived from the generalized formulas newly obtained in the present paper. Numerical discussions are made for the plenum craft (as for the peripheral craft, only an example of results is cited from Ref. 7). Particularly, it will be shown that the stability of the plenum craft might depend on fan, ducting, and powerplant characteristics. In fact, the assumption of the constant total pressure at the fan exit, for example, leads to approximately constant cushion pressure during the oscillation for the plenum craft. This means that the plenum craft are neutrally stable and differs from the observed results. We might say that the consideration of these influences has more significance than ever since the plenum chamber scheme has been currently adopted in practice.

Theoretical Formulations

Unbalanced Operations of Jet and Air Cushion

We shall assume that the oscillatory motion (vertical motion) is slow enough for the quasistatical treatment to be valid and that the compressibility of the air cushion is to be neglected. Due to the volume change of the air cushion during the oscillation, a certain amount of air must be fed into or discharged out of the cushion.

Peripheral Craft

As presented by Tulin,[1] two unbalanced conditions, e.g., the overfed and underfed condition, appear in peripheral jet craft. Let Q_c be the amount of air fed into the cushion in unit time through unit peripheral length; we have the relation (see, for example, Refs. 8 and 9)

$$Q_c = Q_c(h, P_c, J) \tag{1}$$

where h, P_c, and J are the hoverheight, the cushion pressure, and the momentum flux of the jet across the nozzle exit, respectively.

We shall suppose that the weight of the air cushion vehicle is in equilibrium with the cushion lift at $h = h_e$, $P_c = P_{ce}$, and $J = J_e$. Then we have

$$Q_{ce} = Q_c(h_e, P_{ce}, J_e) = 0 \tag{2}$$

Now we shall assume

$$J = \rho t (Q_j/t)^2 = \rho t (Q_f/ct)^2 \tag{3}$$

where t, c, and ρ are the nozzle thickness, the peripheral length of the nozzle, and the density of air, respectively, and Q_j is the volume flow rate of the jet leaving unit peripheral length of the nozzle exit, which is supposed to be equal to Q_f/c, Q_f being the volume flow rate of the fan.

From Eqs. (1) and (3), we have

$$Q_c = Q_c(h, P_c, Q_f) \tag{4}$$

In addition to Eq. (4), we obtain from the hydrodynamic consideration of the jet motion the relation

$$P_c = P_c(h, P_j, J) \tag{5}$$

where P_j is the total pressure of the jet at the nozzle exit and represented by

$$P_j = P_f - \zeta \frac{\rho}{2} \left(\frac{Q_f}{S_f} \right)^2$$

where S_f is the fan exit area, P_f is the total pressure just behind the fan, and ζ is the duct loss coefficient. Then we have

$$P_c = P_c(h, P_f, Q_f) \tag{6}$$

Plenum Chamber Craft

The volume flow rate of air leaving the cushion is $hC_d\sqrt{2P_c/\rho}$ where C_d is the discharge coefficient, and we have

$$Q_c = Q_f/c - hC_d\sqrt{2P_c/\rho} \tag{7}$$

where c is the peripheral length of the effective base area (denoted by S) of the plenum craft. Equation (7) may also be represented in the general expression Eq. (4) obtained for the peripheral craft.

We also have

$$P_c = P_f - \zeta \frac{\rho}{2} \left(\frac{Q_f}{S_f} \right)^2 \tag{8}$$

which may be represented by Eq. (6).

Derivation of Stability Derivatives

The rate of change of the air cushion volume $S\dot{h}$ must be compensated by cQ_c and we have

$$Q_c = S\dot{h}/c \tag{9}$$

where $(\dot{\ })$ represents a derivative with respect to time.

We shall represent the performance characteristics of the fan by

$$P_f = P_f(Q_f, n_f) \tag{10}$$

$$L_f = L_f(Q_f, n_f) \tag{11}$$

where n_f and L_f are the rotational speed and the shaft horsepower of the fan, respectively.

We shall represent the performance characteristics of the powerplant by

$$L_p = L_p(n_p, \phi_1, \phi_2, \ldots) \tag{12}$$

where L_p and n_p are the shaft horsepower and the rotational speed of engines, respectively, and ϕ_1, $\phi_2, \ldots,$ are the parameters which assign the operation condition of powerplants. In what follows, we shall consider, for simplicity, reciprocating engines and represent L_p by

$$L_p = L_p(n_p, \phi) \tag{13}$$

where ϕ is a parameter representing the position of the throttle valve.

Denoting the reduction ratio by κ, and the transmission efficiency by η_t, we have

$$n_p = \kappa n_f \tag{14}$$

$$L_f = \eta_t L_p \tag{15}$$

Equations (4), (6), (9-11), and (13-15) constitute a system of equations for eleven quantities h, $\dot{h}$, P_c, P_f, Q_c, Q_f, n_f, n_p, L_f, L_p, and ϕ, and it might be possible to represent any of eight quantities in terms of three other quantities; say h, $\dot{h}$, and ϕ. Under certain circumstances, this might be performed graphically or numerically. In what follows, we shall consider small oscillations and linearize the equations, which enables us to solve the equations analytically. We shall represent the instantaneous values of a quantity x_i and a function $A(x_1, x_2, \ldots)$ by

$$x_i = (x_i)_e + \delta x_i \tag{16}$$

$$A = A_e + \sum_i \left(\frac{\partial A}{\partial x_i} \right)_e \delta x_i \tag{17}$$

where the subscript e means that the quantity shall be evaluated at the equilibrium condition $h=h_e$, $P_c=P_{ce}$,.., and δx_i is the increment of x_i over the equilibrium condition.

Substituting the expressions like Eqs. (16) and (17) into eight basic equations and eliminating seven small quantities other than δh, $\delta \dot{h}$, δP_c and $\delta\phi$, we obtain

$$\delta P_c = P_{ch}\delta h + P_{c\dot{h}}\delta\dot{h} + P_{c\phi}\delta\phi \tag{18}$$

where

$$P_{ch} = \frac{1}{D}\left[\frac{\partial Q_c}{\partial Q_f}\frac{\partial P_c}{\partial h}\left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right) - F\frac{\partial Q_c}{\partial h}\right] \tag{19}$$

$$P_{c\dot{h}} = \frac{SF}{cD} \tag{20}$$

$$P_{c\phi} = \frac{\eta_t}{D}\frac{\partial Q_c}{\partial Q_f}\frac{\partial P_c}{\partial P_f}\frac{\partial P_f}{\partial n_f}\frac{\partial L_p}{\partial \phi} \tag{21}$$

and

$$F = \left(\frac{\partial P_c}{\partial Q_f} + \frac{\partial P_f}{\partial Q_f}\frac{\partial P_c}{\partial P_f}\right)\left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right) - \frac{\partial P_c}{\partial P_f}\frac{\partial P_f}{\partial n_f}\frac{\partial L_f}{\partial Q_f} \tag{22}$$

$$D = \frac{\partial Q_c}{\partial Q_f}\left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right) + F\frac{\partial Q_c}{\partial P_c} \tag{23}$$

where the derivatives shall be evaluated at the equilibrium condition.

In usual operations of the air cushion vehicle, the throttle valve position is kept fixed during the oscillations, and we have

$$\delta\phi = 0$$

and

$$\delta P_c = P_{ch}\delta h + P_{c\dot{h}}\delta\dot{h} \tag{24}$$

It can be seen from Eqs. (18-23) that not only the cushion characteristics $\partial Q_c/\partial Q_f$, $\partial Q_c/\partial P_c$, $\partial Q_c/\partial h$, $\partial P_c/\partial P_f$, $\partial P_c/\partial Q_f$, $\partial P_c/\partial h$, but also the fan characteristics $\partial P_f/\partial Q_f$, $\partial P_f/\partial n_f$, $\partial L_f/\partial Q_f$, $\partial L_f/\partial n_f$, the duct loss coefficient ζ, and the powerplant characteristics $\partial L_p/\partial n_p$, $\partial L_p/\partial\phi$, η_t, κ affect the cushion stability of the air cushion vehicle.

From Eqs. (4), (6), (10), (11), and (13-15), we also have

$$F\delta Q_f = \left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right)\left(\delta P_c + \frac{\partial P_c}{\partial h}\delta h\right) \tag{25}$$

$$F\delta P_f = \left[\frac{\partial P_f}{\partial n_f}\frac{\partial L_f}{\partial Q_f} - \frac{\partial P_f}{\partial Q_f}\left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right)\right]\left(\delta P_c - \frac{\partial P_c}{\partial h}\delta h\right) \tag{26}$$

We shall consider two special cases, that is, the case of constant volume flow (approximately constant jet momentum flux in peripheral jet crafts) and of constant total pressure.

In the former case, we have, for example,

$$\frac{\partial L_f}{\partial n_f} = \kappa\eta_t\frac{\partial L_p}{\partial n_p}$$

and in the latter case, we have, for example,

$$\frac{\partial P_f}{\partial n_f}\frac{\partial L_f}{\partial Q_f} = \frac{\partial P_f}{\partial Q_f}\left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right)$$

The situation under which these relations hold is very exceptional and almost never occurs. This suggests that the influences of the fan, ducting, and powerplant characteristics are very important.

Numerical Examples

Peripheral Craft

We can express Eq. (1) in a linearized form such as

$$\delta Q_c/\sqrt{J_e t/\rho} = m_h\delta(h/t) + m_p\delta(P_c t/J) \tag{27}$$

It has been frequently mentioned by many researchers[1-5] that the coefficients m_h and m_p take different values according to whether the jet is underfed or overfed. As suggested by Eames,[2] this is a consequence of the neglect of the viscosity of air. Chaplin[10] and Shan-fu-shen[11] attempted to analyze viscous jets in an equilibrium condition. Matsuo improved the method and extended it to include unbalanced jets.[8] In Ref. 9 it was also demonstrated that m_h and m_p were really constants independent of the mode of the jet operation, and semiempirical formulas for m_h and m_p together with the numerical tables were presented. Mathematical formulations for the stability of the peripheral craft are developed in Ref. 7. The formulas presented in Ref. 7 will be derived also from the generalized formulas presently given in Eqs. (19-23). In fact, it will be done by using Eq. (27) for Eq. (1) and assigning an appropriate form to the function $P_c(h,P_j,J)$ in Eq. (5). (The form of P_c depends on the peripheral jet theory adopted. In Ref. 7 the exponential theory[12] is used.) The resulting formulas will not be repeated here, and only a result of examples which show an overall effect of fan, ducting, and powerplant characteristics is cited from Ref. 7 and given in Fig. 1.

In Fig. 1, two theoretical curves and an experimental curve obtained from forced oscillation tests are shown. One of the theoretical curves is calculated assuming the constant momentum flux and the other is calculated by considering the effects of fan, etc. We can see from this that, by considering the effects of fan, etc., the theoretical result is improved.

Plenum Craft

Substituting Eqs. (7) and (8) into Eqs. (22) and (23), we have

$$F = \left(\frac{\partial P_f}{\partial Q_f} - \zeta\rho\frac{Q_{fe}}{S_f^2}\right)\left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right) - \frac{\partial P_f}{\partial n_f}\frac{\partial L_f}{\partial Q_f} \tag{28}$$

$$D = \frac{1}{c}\left(\frac{\partial L_f}{\partial n_f} - \kappa\eta_t\frac{\partial L_p}{\partial n_p}\right) - \frac{C_d h_e}{\sqrt{2\rho P_{ce}}}F \tag{29}$$

From Eqs. (19-21), we have

$$P_{ch} = \frac{F}{D}C_d\sqrt{2P_{ce}/\rho} \tag{30}$$

$$P_{c\dot{h}} = \frac{SF}{cD} \tag{31}$$

$$P_{c\phi} = \frac{\eta_t}{D}\frac{1}{c}\frac{\partial P_f}{\partial n_f}\frac{\partial L_p}{\partial\phi} \tag{32}$$

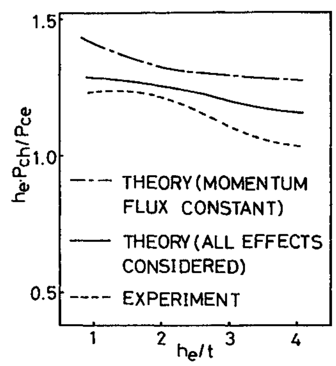

Fig. 1 Stability derivative P_{ch} of a peripheral craft (cited from Ref. 7).

We shall define dimensionless quantities such as

$$\xi = 4Q_f/(\pi^2 d^3 n_f)$$

$$\psi = 2P_f/(\rho\pi^2 d^2 n_f^2)$$

$$\lambda_f = 8L_f/(\rho\pi^4 d^5 n_f^3)$$

$$\lambda_p = 8L_p/(\rho\pi^4 V^{5/3} n_p^3)$$

where d is the diameter of fans and V is the stroke volume of engines. Assuming that geometrically similar fans are used, we have

$$\psi = \psi(\xi) \qquad \lambda_f = \lambda_f(\xi)$$

Substituting these expressions into Eqs. (28-32), we obtain for the case of $\delta\phi = 0$

$$G\frac{\delta P_c}{P_{ce}} = -f\frac{h_e}{\sqrt{2P_{ce}/\rho}}\frac{\delta\dot{h}}{h_e} - \frac{\delta h}{h_e} \tag{33}$$

where G and f are dimensionless coefficients defined by

$$G = \frac{\beta}{\alpha}\left(\frac{\mathrm{d}\lambda_f}{\mathrm{d}\xi} - \frac{\gamma}{\beta}\right) \tag{34}$$

$$\alpha = a\left[3(b\lambda_p - \lambda_f) + bn_p\frac{\partial\lambda_p}{\partial n_p}\right]\left(g - \frac{\mathrm{d}\psi}{\mathrm{d}\xi}\right) + a(\xi g - 2\psi)\frac{\mathrm{d}\lambda_f}{\mathrm{d}\xi}$$

$$\beta = \frac{1}{2}\left[a(\xi g - 2\psi) + 2\xi\right]$$

$$\gamma = \left[3(b\lambda_p - \lambda_f) + bn_p\frac{\partial\lambda_p}{\partial n_p}\right]\left[\frac{a}{2}\left(\frac{\mathrm{d}\psi}{\mathrm{d}\xi} - g\right) - 1\right]$$

$$a = cC_d n_f(h_e/d)\sqrt{8\rho/P_{ce}} \qquad b = \eta_t\kappa^3 V^{5/3}/d^5$$

$$g = \pi^2 d^4 \zeta\xi/(8S_f^2) \qquad f = S/(cC_d h_e)$$

Since the coefficients of $\delta\dot{h}$ and δh in Eq. (33) are all positive, the stability depends on the sign and the magnitude of G. It is also to be noted that a positive damping force always acts on a statically stable craft. As we can see from Eqs. (33) and (34), two critical cases, $\alpha = 0$ and $\mathrm{d}\lambda_f/\mathrm{d}\xi = \gamma/\beta$ exist. In the former case, δP_c is zero for arbitrary values of $\delta\dot{h}$ and δh, which means the air cushion vehicle is neutrally stable. On the other hand, δP_c is infinite in the latter case. It should be noted, however, that the assumption of small oscillations is no more valid in the latter case, and we might only say that the absolute values of the stability derivatives might be very large and strong stability or strong instability might appear near $\mathrm{d}\lambda_f/\mathrm{d}\xi = \gamma/\beta$.

To show a numerical example, we shall assume the numerical data as follows;

$$\xi = 0.187 \qquad \psi = 0.723 \qquad \lambda_f = 0.135 \qquad \lambda_p = 277$$

$$a = 0.447 \qquad b = 0.000500 \qquad f = 62.9 \qquad g = 3.26$$

$$n_p(\partial\lambda_p/\partial n_p) = -1300$$

In selecting the data, an SRN4-class air cushion vehicle has been assumed, and four 3.5- m diam fans and four 25-liter reciprocating engines are assumed to be installed. The values of ξ, ψ, and λ_f have been taken from the characteristic curves of the SRN4 fan given in Fig. 3.2 of Ref. 12, and they are, in fact, the values which give the maximum fan efficiency in the same figure. In the calculation of a, b, f, and g, the values

$$S = 175\,\mathrm{m}^2 \quad c = 26\,\mathrm{m} \quad S_f = 8.5\,\mathrm{m}^2 \quad d = 3.5\,\mathrm{m} \quad h_e = 0.2\,\mathrm{m}$$

$$P_{ce} = 244\,\mathrm{kg/m}^2 \quad n_f = 527\,\mathrm{rpm} \quad C_d = 0.535 \quad V = 0.025\,\mathrm{m}^3$$

$$\kappa = 5 \qquad \eta_t = 0.96 \qquad \zeta = 6.8$$

are assumed, where S and c are taken as a quarter of the total S and c, respectively. The results of the calculations are shown in Fig. 2, which shows the effect of varying the slope of the fan characteristic curves on the stability. As we can see from the figure, the critical lines, $\alpha = 0$ and $\mathrm{d}\lambda_f/\mathrm{d}\xi = \gamma/\beta$ $(G = 0)$ are, in fact, the boundary lines across which the transition from stability to instability occurs. In particular, across the line, $G = 0$, the transition from the strong stability to the strong instability might occur. This suggests that, under certain circumstances, an abrupt change from the stable condition to the unstable condition might occur as a consequence of a small change of the fan characteristics. In Fig. 3, the effect of varying the duct-loss coefficient is shown, from which we can see that, in the present example, the stable region extends as ζ decreases. In Fig. 4, is also shown the effect of varying the slope of the engine characteristic curve. We can see from these figures that the stability is determined to a great extent by the combination of the slope of the total pressure vs volume flow curve, $\mathrm{d}\psi/\mathrm{d}\xi$, and the slope of the

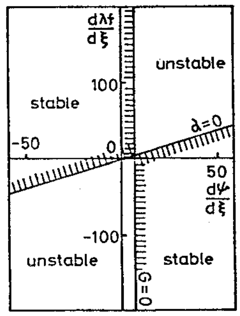

Fig. 2 Effect of the slope of fan characteristic curve on stability.

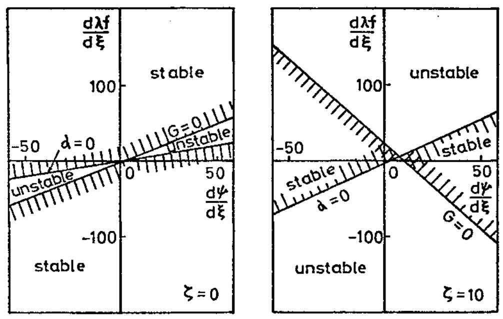

Fig. 3 Effect of the duct loss coefficient on stability. Hatched area indicates the stable region; $\kappa = 5.0$, $n_p\partial\lambda_p/\partial n_p = -1300$.

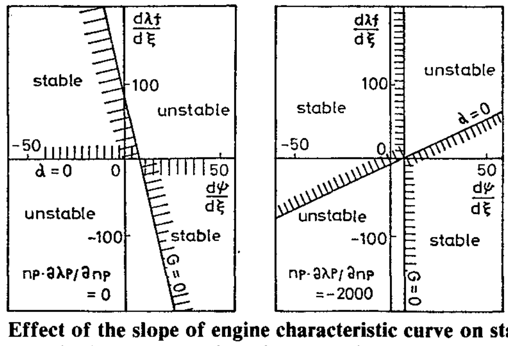

Fig. 4 Effect of the slope of engine characteristic curve on stability. Hatched area indicates the stable region; $\zeta = 6.8$, $\kappa = 5.0$.

shaft horsepower vs volume flow curve, $d\lambda_f/d\xi$. Particularly, it is suggested that, over a wide range of variations of the duct loss and the powerplant characteristic, the stability might be secured by fans with small positive $d\lambda_f/d\xi$, since, usually, $d\psi/d\xi$ is negative. From Fig. 4, we can also see that the effect of the powerplant characteristic is not very significant.

Concluding Remarks

A theoretical study has been made on the cushion stability of vertically oscillating air cushion vehicles including the peripheral and the plenum chamber craft. In the analysis, the influences of fan, ducting, and powerplant characteristics are fully considered. It has been shown that these influences are very important, and that the assumptions of constant momentum flux of the jet or constant total pressure at the nozzle exit during the oscillation are not valid in general; in fact, the circumstance under which these assumptions are valid seldom occurs. It has also been shown that a positive damping force always acts on a statically-stable plenum chamber craft. A numerical example suggests that, under certain circumstances, an abrupt change from the stable condition to the unstable condition might occur as a consequence of a small change of the fan characteristics. It has also been shown that the stability is determined to a great extent by the combination of the slope of the total pressure vs volume flow curve of fans and the slope of the shaft horsepower vs volume flow curve. Particularly, it is suggested that, over a wide range of variations of the duct loss and the powerplant characteristics, the stability might be secured by fans with small positive slopes of shaft horsepower vs volume flow curve. It is also shown that the stable region extends as the duct loss decreases, and that the effect of the powerplant characteristics is not very significant.

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