Suppression of Variation in Cushion Pressure for SES Using Vertically Moving Nozzles

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(Received September 15th, 2009)

In this paper, variation in cushion pressure is investigated theoretically to achieve SES ride comfort. A simple and practical control method is proposed to control cushion pressure changes caused by pumping that appears in SES cruising over waves. Cushion pressure is controlled by varying the discharge height of the vertical nozzle. In this method, the nozzle height (hover height) is kept constant according to craft motion. As the result of investigations, cushion pressures are controlled successfully by the proposed method. In addition, we show that the pressure variation depends both on hover heights and on the rates of change in cushion volume. Therefore, it is necessary to consider phase differences between craft motion and vertical nozzle displacements.

Key Words: SES, Air Cushion, Pressure Control, Nozzle

1. Introduction

Air cushion vehicles (ACVs) are supported by an air cushion and are nearly divorced from traveling surfaces. Contact drag is very small, producing improved transport efficiency. On the other hands, when traveling over surface undulation, a phenomenon called wave pumping is caused by the change in hover height and cushion volume. In larger classes of ACVs, ride control uses vents with valves. This releases air from the cushion to the atmosphere when cushion pressure increases. It is effective when cushion pressure increases but not when it decreases. Moreover, the dynamic characteristics of air-supply systems become important to instantly recover the cushion pressure reduced by the discharge to the atmosphere.

Similar wave pumping appears in surface-effect ships (SES). The rear ends of the cushion are usually sealed by bag skirts or robe seals. Contact between seals and traveling surfaces occurs, causing contact drag. Water contact not only causes drag but also causes wear of skirt materials. The latter causes practical problems of maintenance and replacement of seals.

In previous reports, we proposed a method to control cushion pressure by changing the discharge angle of the nozzle with changes in cushion pressure.1,2) Satisfactory results were obtained both theoretically and experimentally. However for practical applications it is necessary to estimate the required variation of the discharge angle in advance.

This report proposes an alternative method where cushion pressure is controlled by changing the vertical position of the nozzle, that is, by changing the nozzle height (hover height). The vertical craft displacement itself is an estimate of the required change of nozzle height in this case. From a practical view point this method might be superior to the previous method. Theoretical analysis of the method is presented and relations between nozzle height and variation in cushion pressure are investigated. Comparisons with experiments shows that the method gives useful results.

2. Control of Cushion Pressure

A model of the SES considered here is shown in Fig. 1. A SES has both an air cushion like an ACV and twin hulls. In this report, conventional finger skirts are fitted at the bow and the proposed nozzles are fitted at the stern. The nozzle moves vertically and independently to craft motion. Both sides of the cushion are sealed by rigid walls (hulls). The cushion is then sealed by the skirt at the bow, the jet at the stern and rigid walls at both sides. The jet blown from the nozzle impinges on the supporting surface, builds a cushion and then flows out to the atmosphere.

The jet has three different operation modes according to the craft motion. When the craft is stationary, the jet is in equilibrium with the cushion and flows out tangentially to the supporting surface as shown in the center of Fig. 2. When the craft is moving, both hover height and jet operating conditions change. Jet operations are not in equilibrium with the cushion but take one of two operational modes: overfed or underfed. In overfed conditions, the jet is stronger than required to seal the cushion and a part of the jet flows into the cushion. This happens when the SES is moving upwards and the cushion volume is increasing. In underfed conditions, the jet is weaker than the required strength and air escapes out of the cushion. This happens when the SES is moving downwards and cushion volume...
is reducing. Changes in cushion pressure are affected by craft velocity and hover height.

A new method is proposed to control cushion pressure, keeping it almost constant during oscillation by moving nozzles vertically and thus keeping hover heights almost constant. When the cushion pressure decreases, the nozzle is moved downwards to suppress the outflow of air from the cushion and recover the reduced pressure as shown in the left side of Fig. 2. On the other hand, when cushion pressure increases, the nozzle is moved upwards. The outflow of air from the cushion is enhanced as shown in the right side of Fig. 2, suppressing the pressure increase. Apparently, it seems that vertical displacement of the nozzle that is equal to but in the opposite direction of the craft displacement cancels pressure changes. However, there is another factor that affects pressure change, the effect of craft velocity. This is examined by numerical investigations. Another merit of the method is that water contact is reduced to a large degree by keeping hover height almost constant.

3. Theoretical Analysis

3.1. Theoretical model

A model of an SES moving vertically above the supporting surface is shown in Fig. 3. The position of the model is represented by $H(t)$ where $t$ represents time. A nozzle with thickness $t_N$ is fitted at the right end. The distance between the lower end of the nozzle and the bottom of the model, that is the nozzle length, is represented by $H_N(t)$. The hover height $h(t)$ is then represented by

$$h(t) = H(t) - H_N(t)$$

3.2. Characteristics of jet operations

The jet performance is analyzed using the exponential theory described previously.\(^2\)

According to the exponential theory, the following equations hold despite jet operating modes

$$\frac{P_c}{H_j} = 1 - e^{-2X}$$

$$\frac{Q}{\sqrt{H_j}} = \sqrt{\frac{2}{\rho X}} \frac{t_N}{(1 - e^{-X})}$$

$$\frac{J}{H_j} = \frac{t_N^2}{X} (1 - e^{-2X})$$

where, $P_c$ is the cushion pressure, $t_N$ is the nozzle thickness, $H_j$ is the total pressure of jets, $Q$ is the volume flow rate of jet, $\rho$ is the density of air, $J$ is the momentum flux of jet, $R_j$ is the radius of curvature of curved jet and $X = \frac{t_N}{R_j}$.

(i) Balanced condition

In the balanced condition, when the jet is completely balanced with the air cushion, $X$ is represented by

$$X = \frac{t_N}{R_j} = X_c$$

(ii) Underfed condition

In the underfed condition, the following equation holds where $\Delta Q$ is the quantity of air flowing into cushion.

$$\frac{\Delta Q}{\sqrt{H_j}} = - \frac{\sqrt{2}}{\rho X} \left( h - \frac{t_N}{X} \right) \sqrt{1 - e^{-2X}}$$

Actually, $\Delta Q$ takes negative values in the underfed condition.

(iii) Overfed condition

In the overfed condition, the following equation holds.

$$\frac{\Delta Q}{\sqrt{H_j}} = \frac{\sqrt{2}}{\rho X} \left( 1 - \frac{1}{2} \left( 1 - e^{-2X} \right) \left( 1 + \frac{h}{t_N X} - e^{-X} \right) \right)$$

These three jet operation modes are discriminated by values of the parameter $X$. Using $X_c$, the value of $X$ at the balanced condition, they are discriminated as follows:

- When $X = X_c$, balanced condition
- When $X > X_c$, underfed condition
- When $X < X_c$, overfed condition
3.3. Analysis of vertical motions

Based on the quasistatic viewpoint, we applied the above expressions to the analysis of SES vertical motion. From the conservation of mass, the rate of change of the cushion volume $BH(t)$ is compensated by $\Delta Q$, the air inflow into the cushion where $B$ is the width of the cushion, that is

$$\Delta Q = BH(t)$$  (8)

The air supply system consists of a fan and duct. Considering duct losses, we have

$$H_t = H_0 + \xi \frac{\rho}{2} \left( \frac{Q_t}{S_f} \right)^2$$  (9)

where, $H_t$ is the total pressure produced by fan, $Q_t$ is the volume flow rate of the fan, $\xi$ is the duct loss coefficient, and $S_f$ is the cross-sectional area at the fan exit.

The fan characteristic is represented by

$$H_t = H_t(Q_t, n_t)$$  (10)

where, $n_t$ is the fan rotation speed. We assume that $n_t$ is a constant during oscillation. To consider varying $n_t$, we may only add the characteristic of the driving system, e.g., engine, to the above equations.

We assume that the vertical motion of the model is expressed by a simple harmonic motion as

$$H(t) = H_0 + \Delta H \sin \left( \frac{2\pi t}{T} \right)$$  (11)

where, $H_0$ is the distance between the model and the supporting surface at $t = 0$, $\Delta H$ is the amplitude of oscillation, and $T$ is the period.

We change the nozzle length $H_N$ sinusoidally with a phase difference $\delta$ with model motion.

$$H_N(t) = H_{N0} + \Delta H_N \sin \left( \frac{2\pi t}{T} (t - \delta) \right)$$  (12)

where, $\Delta H_N$ is the amplitude of nozzle length.

We define the volume flow coefficient $\xi$ and the total pressure coefficient $\psi(\xi)$ as follows:

$$\psi(\xi) = 2H_0/(\rho\pi^2d^2n_t^2)$$  (13)

$$\xi = 4Q_t/(\pi^2d^3n_t), \quad Q_t = QL_c$$  (14)

where, $d$ is the diameter of the fan, and $L_c$ is the length of the nozzle.

In the underfed condition, from Eqs. (3), (6) and (8), we obtain

$$\frac{BH}{Q} = \frac{1}{1 - e^{-X}} \left( 1 - \frac{h}{l_N} X \right) \sqrt{1 - e^{-2X}}$$  (15)

From Eq. (14), we obtain

$$Q = \frac{\xi \pi^2 d^3 n_t}{4L_c}$$  (16)

Eliminating $Q$ between Eqs. (15) and (16), we obtain

$$F(\xi, X) = \frac{\xi \pi^2 d^3 n_t}{4L_c(1 - e^{-X})} \left( 1 - \frac{h}{l_N} X \right) \sqrt{1 - e^{-2X}} - BH$$

$$= 0$$  (17)

This represents the jet characteristic in the underfed condition.

Similarly from Eqs. (3), (7), (8) and (16), we obtain the characteristic equation for the overfed condition.

$$F(\xi, X) = \frac{\xi \pi^2 d^3 n_t}{4L_c(1 - e^{-X})}$$

$$\times \left\{ 1 - \frac{1}{2}(1 - e^{-2X}) \left[ 1 + \frac{h}{l_N} X - e^{-X} \right] \right\}$$

$$- BH = 0$$  (18)

Considering $Q = Q_t/L_c$, from Eq. (3), we obtain

$$H_j = \frac{\rho}{2} \left( \frac{Q_t}{S_f} \right)^2 \left( \frac{S_t}{L_c l_N} \right)^2 \left( \frac{X}{1 - e^{-X}} \right)^2$$  (19)

Eliminating $H_j$ between (9) and (19), we obtain

$$H_t = \frac{\rho}{2} \left( \frac{Q_t}{S_f} \right)^2 \left( \xi + \frac{S_t}{L_c l_N} \left( \frac{X}{1 - e^{-X}} \right)^2 \right)$$  (20)

From Eq. (13), we obtain

$$H_t = \frac{\psi(\xi)\rho\pi^2 d^2 n_t^2}{2}$$  (21)

From Eq. (14), we obtain

$$Q_t = \frac{\xi \pi^2 d^3 n_t}{4}$$  (22)

Inserting Eqs. (21) and (22) into Eq. (20), we obtain

$$F_\psi(\xi, X) = \frac{\xi \pi^2 d^3 n_t}{16S_f^3} \left( \xi + \left( \frac{S_t}{L_c l_N} \right)^2 \left( \frac{X}{1 - e^{-X}} \right)^2 \right) - \psi(\xi)$$

$$= 0$$  (23)

Solving simultaneous Eqs. (17) and (23), we obtain $\xi$ and $X$ for the underfed condition. Similarly, solving Eqs. (18) and (23), we obtain $\xi$ and $X$ for the overfed condition.

From Eqs. (2), (3) and (14), we obtain

$$P_c = \frac{\rho}{2} \left( \frac{\xi \pi^2 d^3 n_t}{4L_c l_N} \right)^2 \left( \frac{X}{1 - e^{-X}} \right)^2 \left( 1 - e^{-2X} \right)$$  (24)

Inserting $\xi$ and $X$ into Eq. (24), we obtain the cushion pressure $P_c$. Note $\psi(\xi)$ is approximated by a polynomial expression constructed from $\xi$ in the calculations.

4. Results and Discussions

As preliminary tests we consider two cases to hold cushion pressure by adjusting the nozzle length (hover height) according to model motion. In one case, only the model heights change with constant nozzle lengths; in the other, nozzle lengths change with constant model heights. Finally, by combining the two results we discuss the feasibility of the proposed method.

A set of typical values used in the calculations are as follows:
3) reported experiments.

The mean hover height of the model measured from the supporting surface is 100 mm (period of oscillation). The mean height of the model measured from the supporting surface, i.e., the mean hover height is 30 mm (h/\(f_N = 1.5\)). We can see that for longer periods there are no phase differences between the change in hover height and the variation in cushion pressure but phase differences become noticeable for shorter periods. This suggests that effects of oscillating speeds might appear in connection with change in cushion volume. It can also be seen that abrupt upward movements bring abrupt decreases in cushion pressure. This might occur because the air supply from the fan cannot keep up with the abrupt increase in cushion volume. In fact, such abrupt decreases in pressure do not appear with reduced cushion areas reduced change in cushion volume.

4.1. Oscillating model with constant nozzle length

Figure 4 shows the variation in cushion pressure where the model oscillates with constant nozzle lengths for various periods of oscillation. The mean height of the model measured from the supporting surface is 100 mm (\(H_0/f_N = 5.0\)), the amplitude of the model is 10 mm (\(\Delta H/f_N = 0.5\)), and the mean distance from the lower edge of the nozzle to the supporting surface, i.e., the mean hover height is 30 mm (h/\(f_N = 1.5\)). We can see that for longer periods there are no phase differences between the change in hover height and the variation in cushion pressure but phase differences become noticeable for shorter periods. This suggests that effects of oscillating speeds might appear in connection with change in cushion volume. It can also be seen that abrupt upward movements bring abrupt decreases in cushion pressure. This might occur because the air supply from the fan cannot keep up with the abrupt increase in cushion volume. In fact, such abrupt decreases in pressure do not appear with reduced cushion areas reduced change in cushion volume.

Figure 5 shows the variations in cushion pressure with a period of 1.0 s for various model amplitudes (\(\Delta H/f_N = 0.25 \sim 1.0\)). Nonlinearities appear for large amplitude oscillations even in long-period oscillations. This is noticeable when cushion pressure increases at downward motion of the model.

4.2. Varying nozzle heights with stationary model

Figure 6 shows the changes in cushion pressures with stationary model when only nozzle heights are varied for various amplitudes. Model height measured from the supporting surface is 100 mm and the mean distance from the lower edge of the nozzle to the supporting surface, i.e., the mean hover height is 30 mm. Changes in hover heights are the same in Fig. 5 and Fig. 6, but the difference is that only the model moves in the former and only the nozzle moves in the latter. The changes in cushion pressure are similar to Fig. 5 and Fig. 6, and it is expected that changes in cushion pressure might be controlled to some extent by combining the two. However, for fine control, setting of phase differences between model motion and nozzle displacements is required because the change in cushion volume appears in the form \(H(t)\) as shown in Eq. (8). It might be especially necessary at shorter periods.

4.3. Control of cushion pressure

From the above results, control of cushion pressure was attempted by moving the nozzle with phase differences for model motion. The results are shown in Fig. 7 for a period of 1.0 s and in Fig. 8 for 0.25 s. In each case, the mean height of the model is 100 mm, the mean hover height is 30 mm, and the oscillation amplitudes of the model and the nozzle are 10 mm. In these figures “Uncontrolled” means uncontrolled cases with constant nozzle height. “Controlled-1” is when nozzle heights are changed with amplitudes equal to those of model motions. In “Controlled-2”, phase differences of 2% are added to “Controlled-1” cases. “Controlled-3” in Fig. 7 is when the amplitude of nozzle height is 1% larger than “Controlled-1” case and a phase difference of 2.3% is added. In “Controlled-3” of Fig. 8, the amplitude is 2.4% larger and the phase difference is 14%. Figure 7 shows that in “Controlled-1” cushion pressure variation is suppressed to 15% of the “Uncontrolled” case and that effects of phase difference are very small. In these cases of Fig. 7, the ranges of variation in cushion pressure versus the amplitudes of nozzle heights are shown in Fig. 9. We can see from this that changes in cushion pressures are minimum when the ampli-
The amplitude of the nozzle is equal to the amplitude of the model. This suggests that at smaller amplitudes and longer periods only varying nozzle heights with amplitudes nearly equal to model amplitudes is sufficient. However, Fig. 8 suggests that at shorter periods, adjustments of nozzle heights are insufficient but adding phase differences are essential. From Figs. 7 and 8, we might conclude that the proposed method is useful for practical purposes.

4.4. Comparison with experiments

Figure 10 compares computed results with experimental results where the mean distance between the model and supporting surface is 100 mm, the amplitude of the model is 15 mm, the mean hover height is 30 mm, and the period is 1.0 s. In Fig. 10, calculations have been made without phase differences. We can see that the proposed method suppresses the variation in cushion pressure effectively and suggests its feasibility.

5. Conclusions

We propose a method to control pressure changes in SES cruising over waves and examine its feasibility. A vertical nozzle is fitted at the stern and is moved vertically with the same amplitude but opposite direction to model motion so hover height is kept approximately constant during motion. The method gives good results when the periods of model motion are moderate, but at shorter periods, phase differences between model motion and changes of nozzle heights must be set, because the rate of change in cushion volume involves the speed of model motion $H(t)$. In fact, cushion pressure is well controlled by setting phase differences even at shorter periods.

The results were compared with experimental results and show that the proposed method is feasible for practical purposes. Ride control aims to control craft displacement or acceleration. Control of cushion pressure is essential for this and the proposed method is a useful technique.

Acknowledgments

The authors would like to express their appreciation to Mr. H. Senba, Ms. Y. Eguchi, Mr. M. Ohno, and Mr. K. Yamashita for their help in performing experiments.

References