GROUND-EFFECT THEORY AND ITS APPLICATION TO AIR FLOTATION DEVICES

by

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ABSTRACT

The ground-effect theories, originally developed for air cushion vehicles (or ground-effect machines), are re-examined and compared with the air bar test results. The geometries of the tested air bars are different from that of the basic ground-effect model. It is shown that the ground-effect theories can be applied to the air bars by using properly defined equivalent values of the ground-effect variables. The ground-effect theories are applied to a tilted flexible web, and the equations for lateral aerodynamic force are derived. The discussion in this paper is limited to the pressure-pad-type air bars.

INTRODUCTION

Various types of air flotation devices are widely used for non-contact support of webs [1-4]. The major purposes of using non-contact supporting devices are to prevent damage to the coated or printed surfaces of web during drying processes, to reduce friction drag at the support, or to change the direction of web motion. Two major problems in air flotation devices are lateral instability and flutter of webs. It is known that the lateral instability occurs mainly when the web is cambered (that is, the web has an in-plane curvature) and the total length to width ratio of the oven is large, for example, greater than 40. A cambered web always tends to move toward the short-span side.

To analyze lateral instability of a floated web, Shelton [5] introduced the concept of "specific stiffness," which corresponds to the machine-directional tensile stiffness, and showed that the in-plane bending of web cannot be solved by classical methods. Lateral deflection of a uniform or non-uniform web caused by the cross-directional tilt angle was studied by Swanson [6]. Moretti and Chang [7] showed the connection between the out-of-plane perturbations and lateral stability in three different ways: equivalent beam stiffness, geometric coupling, and induced lateral force. These analytical models of lateral stability require equations for aerodynamic forces at the support bars, that are not easily available.

Aerodynamic forces on a rigid web were measured by Pinnamaraju [8] for various air bars. He studied the effect of flotation height on the aerodynamic forces and explained the out-of-plane stability characteristics of webs. Purdue [9] studied the effects of the machine-directional tilt angle of a rigid web. He also demonstrated flow instability phenomena by injecting a dye in a water-emitting air bar immersed in water. Nisankararao [10] studied the effects of cross-directional tilt angle of a rigid web which might be the major cause of lateral instability of a web in an air flotation oven.

In this paper, the ground-effect theories, which were originally developed in connection with the development of hovercrafts in 1950' and 1960', are re-examined and compared with the air bar test results. Then the ground-effect theories are applied to a tilted flexible web, and the equations for lateral aerodynamic force are derived.

GROUND-EFFECT THEORIES

Thin Jet Theory

The basic ground-effect model is shown in Figures 1 and 2. For modeling of the aerodynamic forces, it is assumed that

(1) the thickness of jet flow is much smaller than the flotation height,
(2) the thickness of jet flow does not change along the path of jet,
(3) the flow profile across the jet is uniform and the jet speed does not change along the path of jet,
(4) the path of jet flow has a constant curvature and is tangent to the ground as shown in Figure 2, and
(5) the pressure inside the region surrounded by the two streams of air jet is constant.

The validity of the assumptions and derivation of the ground-effect equations are discussed also by Mair [11], Jaumotte and Kiedrzynski [12], and Davies and Wood [13]. The fourth assumption yields

$$h = r(1 + \cos\theta) \tag{1}$$

where h is the flotation height, r is the radius of flow path, θ is the angle of ejection. The centripetal force balance requires

$$\frac{\rho b V_{jet}^2}{r} = p_c \tag{2}$$

where ρ is the air density, b is the width of jet stream, V_{jet} is the velocity of jet, P_c is the cushion pressure. The horizontal force balance requires

$$\rho b V_{jet}^2 (1 + \cos\theta) = p_c h \tag{3}$$

which can also be derived by combining Eq. (1) and Eq. (2). This equation can be rewritten as

$$p_c = \rho V_{jet}^2 \frac{b}{h}(1 + \cos\theta) = \frac{J}{h}(1 + \cos\theta) \tag{4}$$

where J is the momentum flux per unit length of jet flow, defined by $J \equiv \rho b V_{jet}^2$. The effective total pressure of jet flow at the exit is

$$p_j = \frac{p_c}{2} + \frac{\rho V_{jet}^2}{2} \tag{5}$$

where the static pressure is assumed to be the average of the ambient pressure (zero gage pressure) and the cushion pressure because these two pressures are acting on the two sides of the air jet. Then the momentum flux becomes

$$J \equiv \rho b V_{jet}^2 = \left(2p_j - p_c\right)b \tag{6}$$

From Eqs. (3) and (6), we obtain

$$\frac{p_c}{p_j} = \frac{2(1+\cos\theta)}{h/b + 1 + \cos\theta} \tag{7}$$

which is the coefficient of cushion pressure. Equation (7) indicates that $\frac{h}{b}(1+\cos\theta) < 1$, otherwise the pressure developed between the wall and the flotation device becomes greater than the total jet pressure at the nozzle, violating the physical law. For example, if the angle of jet is 30^o, the thin jet theory is valid only when the flotation height is greater than about twice of the thickness of jet flow.

The lift force on a rigid web is

$$F = p_c w + 2J\sin\theta \tag{8}$$

where w indicates the distance between the two nozzles and the last term is the change of momentum of the jet flow in the vertical direction. By substituting Eqs. (6) and (7) into the above equation,

$$\frac{F}{p_j b} = \frac{2(1+\cos\theta)(w/b - 2\sin\theta)}{h/b + 1 + \cos\theta} + 4\sin\theta \tag{9}$$

If we substitute Eqs. (4) and (5) into Eq. (9) we can obtain the equation of lift force normalized by momentum flux,

$$\frac{F}{2J} = \frac{w}{2h}(1+\cos\theta) + \sin\theta \tag{10}$$

which is usually called the coefficient of ground effect.

Thick Jet Theory

The theory of thick jet is discussed in Jaumotte and Kiedrzynski [12] and in Strand [14]. In this study, we follow a procedure similar to Jaumotte and Kiedrzynski. The equation of equilibrium of an element shown in Figure 3 is

$$\left(p+\frac{dp}{dr}\frac{dr}{2}\right)\left(r+\frac{dr}{2}\right)d\phi-\left(p-\frac{dp}{dr}\frac{dr}{2}\right)\left(r-\frac{dr}{2}\right)d\phi-pdrd\phi=\rho rd\phi dr\frac{V_{jet}^2}{r} \tag{11}$$

which can be simplified to be

$$\frac{dp}{dr}=\frac{\rho V_{jet}^2}{r} \tag{12}$$

The Bernoulli equation for the total pressure of the jet flow at the nozzle is

$$p_j=p+\frac{\rho V_{jet}^2}{2} \tag{13}$$

From Eqs. (12) and (13),

$$\frac{dp}{p_j-p}=\frac{2dr}{r} \tag{14}$$

If we integrate the two terms in the above equation,

$$\int_0^{p_c}\frac{dp}{p_j-p}=-ln\left(1-\frac{p_c}{p_j}\right) \tag{15}$$

$$\int_{r_o}^{r_o+b}\frac{2dr}{r}=2ln\left(1+\frac{b}{r_o}\right) \tag{16}$$

By equating the above two equations and using the relationship of $h=b+r_o(1+\cos\theta)$,

$$\frac{p_c}{p_j}=1-\frac{1}{(1+b/r_o)^2}=1-\left(\frac{h/b-1}{h/b+\cos\theta}\right)^2 \tag{17}$$

We can obtain the equations of normalized lift force in two different forms. If we substitute Eqs. (6) and (17) into Eq. (8), and eliminate p_c and J,

$$\frac{F}{p_jb}=\left\{1-\left(\frac{h/b-1}{h/b+\cos\theta}\right)^2\right\}(w/b-2\sin\theta)+4\sin\theta \tag{18}$$

or if we eliminate p_c and p_j,

$$\frac{F}{2J}=\frac{w}{2b}\frac{(h/b+\cos\theta)^2-(h/b-1)^2}{(h/b+\cos\theta)^2+(h/b-1)^2}+\sin\theta \tag{19}$$

Equations (7) and (17), and Eqs. (10) and (19) are compared in Figures 4 and 5 respectively. In those charts, the angle of jet flow is assumed to be 30^o following the test condition of Davies and Wood [13] for comparison. The equations and the test results agree well in the region $h/b > 3$.

COMPARISON OF THEORIES AND EXPERIMENTS

Ground-Effect Experiment

Davies and Wood [13] measured pressure distribution on a rigid plate placed against a test model of ground-effect machine, schematically shown in Figure 1. The angle of jet was 30 degrees, the thickness of air nozzle was 5 mm (0.2 inch), the length of air nozzle was 375 mm (15 inches), and the distance between the two nozzles was 150 mm (6 inches). They also measured the flow profile of the air jet at the nozzle for various flotation heights, and calculated the momentum of the air jet. Comparison of the test results with the theories is straightforward because all the ground-effect variables, except the total pressure of jet flow at the nozzle, are clearly defined in their tests. As demonstrated in Figures 4 and 5, the simple theories are very useful tools to predict the aerodynamic forces for ground-effect machines. Why can such simple theories, especially the thin jet theory which is based on the restrictive assumptions be accurate? The validity of the thin jet model has been a subject of debate for many years and several researchers attempted to extend that simple theory by including the effects of air viscosity or air compressibility. None of those complicated versions of ground-effect theories could add much to the simple model.

Air Bar Experiments

The test data explained in this section are from Pinnamaraju [8] and Nisankararao [10]. The tested air bars are sketched in Figure 6., and typical pressure measurement results are in Figures 7 and 8. It is shown that a peak pressure appears near the air nozzle and the pressure inside a region surrounded by the two air jets is nearly constant. The cushion pressure is a function of the supply pressure, the geometry of air bar, and the flotation height. Figures 9 and 10 show the total lift forces that are obtained by integrating the pressure curves. It is seen that the experiments were not completely reproducible, and in most cases, Nisankararao's results show higher values of aerodynamic force.

Comparison of the test results with the ground-effect theories requires some considerations, because the geometries of the tested air bars are different from the basic geometry of the ground-effect model. In order to compare the theories and the test results, we need to define equivalent values of the ground-effect variables, which are the thickness of jet, the angle of jet, the flotation height, and the total pressure of jet flow at the nozzle or jet velocity.

The effective thickness of jet can be defined by the minimum thickness of air nozzle, as shown in Figure 6. During the tests, only the supply pressure was measured and the flow velocity or flow rate was not measured. For typical air bars, the most uncertain quantity is the angle of air jet. It is observed that when there is no web reacting the aerodynamic force, the jet flow is attached to the surface of the air bar so that the angle of jet is nearly zero. This is the phenomenon usually called "Coanda effect." The "equivalent" values of the angle of jet were calculated based on the locations of peak pressure on the web. For the two air bars, the angle is approximately in the range of 60^o to 80^o. For comparison with the theories, the angle is assumed to be 80^o for all cases. Definition of the flotation height is also uncertain because the exit of jet is lower than the top surface of air bar as shown in Figure 6. Test results show that the flotation height should be defined by the distance between the web and the exit of jet rather than the distance between the web and the air bar surface.

Figures 11 and 12 show the comparison of the theories and the test results for cushion pressure coefficient (p_c/p_j). Figure 11 assumes that the total pressure of jet flow is the same as the supply pressure ($p_j = p_o$), and Figure 12 is based on the assumption that the total pressure of jet flow is the same as the peak pressure on the web ($p_j = p_p$). It is seen that Figure 11 shows more clear trend than Figure 12. A possible reason of this difference is that the peak pressure on the plate may not properly represent the total or dynamic pressure of the jet flow. We need to study re-attachment phenomena of curved jet in order to properly interpret the observation. Figure 11 seems to imply that there are certain phenomena that cause consistent pressure loss or a systematic error. The study of Richardson et al. [15] shows that the measured coefficient of cushion pressure is up to 40% lower than the theoretical prediction when the Reynolds number is low and the flotation height to jet thickness is large. By assuming that the pressure loss coefficient is 28% or $p_j = 0.72p_o$, we obtain Figures 13 through 15.

EFFECTS OF OTHER PARAMETERS

Effects of Viscosity

Bradbury [16] studied the effects of air viscosity on the ground-effect. It was assumed that the jet flow is incompressible and two dimensional, the jet develops like a two-dimensional free jet except that it follows a curved path, the jet momentum is therefore conserved and it can be expressed by $J = (2p_j - p_c)b$, the pressure within the cushion is uniform and the center-line of the jet is a circular arc, the thickness of jet is much smaller than the radius of that circular arc, and from the mass flow considerations, the streamline that originates at the inner edge of the nozzle intersects the ground and the flow divides there. The result of this mixing theory is close to that of the inviscid thin jet theory in a wide range of the jet thickness to flotation height ratio. Bradbury concluded that the good agreement between his mixing theory and the simple inviscid theory is *purely fortuitous* and the good agreement between the inviscid theory and experiments would seem to be *largely fortuitous*.

Effects of Reynolds Number

Richardson et al. [15] tested the effects of Reynolds number ($V_{jet}b/v$), base recess, and nozzle size (b). Refer to Figure 16. The angle of jet flow at the nozzle was fixed at 30^o. The results show that the inviscid theory overestimates the cushion pressure up to

40% at small jet thicknesses, low Reynolds numbers, and high flotation heights. The error is reduced to about 5% (still the theory overestimates) at the opposite conditions.

Effects of Mach Number

Hope-Gill [17] analyzed the effects of high speed jet flow and found that the coefficient of cushion pressure decreases as the Mach number increases. For example, when the flotation height to jet thickness ratio is 2 and 4 (that is, $h/b = 2$ and $h/b = 4$), the coefficient of cushion pressure at sonic speed of jet flow is reduced by 2% and 4% respectively compared to the values at low subsonic cases. In most cases, the air speed at the nozzle of an air bar is less than *100 m/sec*, that is, the Mach number is less than 0.3. Therefore, the effect of Mach number can be neglected for practical purposes.

FLOTATION OF FLEXIBLE WEBS

Aerodynamic Force on a Flexible Web

When a flexible web is floated by an air bar, the major floated portion of the web will have a constant curvature because the pressure developed in the gap between the web and the air bar is nearly constant. Two main differences between the case of a rigid web and that of a flexible web are in the effective angle of jet flow and the effective flotation height. Therefore, if we define the effective angle of jet as $(\theta - \alpha)$ and the flotation height as the minimum distance between the air bar and the web, then we can use the same equation of aerodynamic force discussed in previous sections. Refer to Figure 17.

Lateral Force on a Tilted Flexible Web

Assume that the local aerodynamic force on a tilted web is the same as that on a non-tilted web having the same flotation height. If the web is tilted in the cross direction, the total force generated by one air bar can be obtained by integrating the distributed force along the width of web.

$$\frac{F_t}{p_j b} = \frac{1}{p_j b} \int_0^d F(y) dy \tag{20}$$

If the tilt angle is small, he local flotation height h can be expressed by

$$h = h_{min} + y \tan\beta \approx h_{min} + (h_{max} - h_{min}) y/d \tag{21}$$

For thin jets, by substituting Eq. (9) into Eq. (20) and using the above relationship, the equation of normalized total force on a tilted web becomes

$$\frac{F_t}{p_j bd} = \frac{2b\{1+\cos(\theta-\alpha)\}\left\{\frac{w}{b} - 2\sin(\theta-\alpha)\right\}}{h_{max} - h_{min}} \ln\left\{1 + \frac{h_{max} - h_{min}}{h_{min} + b + b\cos(\theta-\alpha)}\right\} + 4\sin(\theta-\alpha) \tag{22}$$

Its lateral component is

$$\frac{F_{ty}}{p_j bd}=-2\frac{b}{d}\{1+cos(\theta-\alpha)\}\left\{\frac{w}{b}-2\,sin(\theta-\alpha)\right\}ln\left\{1+\frac{h_{max}-h_{min}}{h_{min}+b+b\,cos(\theta-\alpha)}\right\} \\ -\frac{4(h_{max}-h_{min})}{d}sin(\theta-\alpha) \tag{23}$$

For thick jets, Eqs. (18), (20) and (21) yield

$$\frac{F_t}{p_j bd}=\frac{2b\{1+cos(\theta-\alpha)\}\left\{\frac{w}{b}-2\,sin(\theta-\alpha)\right\}}{h_{max}-h_{min}} \\ \times\left[ln\left\{1+\frac{h_{max}-h_{min}}{h_{min}+b\,cos(\theta-\alpha)}\right\}-\frac{h_{max}-h_{min}}{\{h_{max}+b\,cos(\theta-\alpha)\}\{h_{min}+b\,cos(\theta-\alpha)\}}\right] \\ +4\,sin(\theta-\alpha) \tag{24}$$

and the lateral force is

$$\frac{F_{ty}}{p_j bd}=-2\frac{b}{d}\{1+cos(\theta-\alpha)\}\left\{\frac{w}{b}-2\,sin(\theta-\alpha)\right\} \\ \times\left[ln\left\{1+\frac{h_{max}-h_{min}}{h_{min}+b\,cos(\theta-\alpha)}\right\}-\frac{h_{max}-h_{min}}{\{h_{max}+b\,cos(\theta-\alpha)\}\{h_{min}+b\,cos(\theta-\alpha)\}}\right] \\ -\frac{4(h_{max}-h_{min})}{d}sin(\theta-\alpha) \tag{25}$$

Once we know the lateral aerodynamic force on a titled web, we can analyze lateral instability of a web in flotation ovens as briefly mentioned in other paper [7].

CONCLUSIONS

The existing theories of ground-effect were re-examined and applied to the pressure-pad air bars supporting flexible webs. The theories, based on the momentum balance equations, have been proved to be useful tools for predicting the aerodynamic force on a floated web. Equations of lateral force have been obtained from the thin jet model and the thick jet model. The thin jet model is valid when the flotation height is greater than about twice the jet thickness; the thick jet model is more accurate than the other when the flotation height is small.

The aerodynamic characteristics of pressure-pad air bars are determined by four factors: the angle of the air nozzle (angle of jet flow at the nozzle), the thickness of the air nozzle (thickness of jet flow), the width of air bar (distance between the nozzles), and the total pressure of the air jet at the nozzle or the velocity of jet flow. By properly defining the equivalent values of those variables, we can predict the aerodynamic forces on the web floated by an air bar.

When a web is supported by a group of air bars we need to consider some additional factors including the distance between adjacent air bars, the separation distance (height difference) between the upper and lower rows of air bars, and the camber (in-plane curvature) of web. The equations of the aerodynamic forces developed in this study can be used to analyze lateral stability of a web in flotation ovens.

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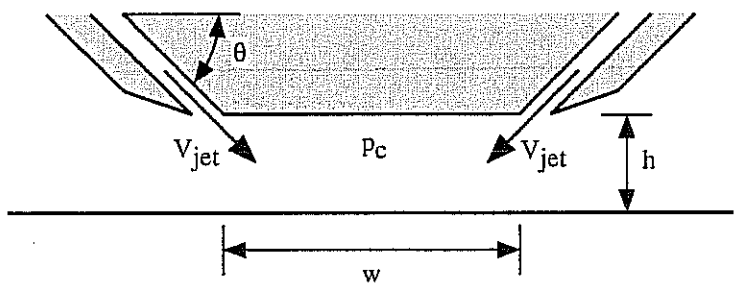


Figure 1 A schematic of ground-effect model

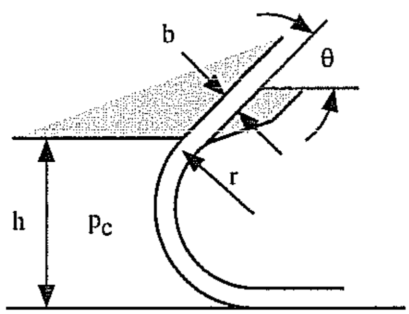


Figure 2 Thin jet model

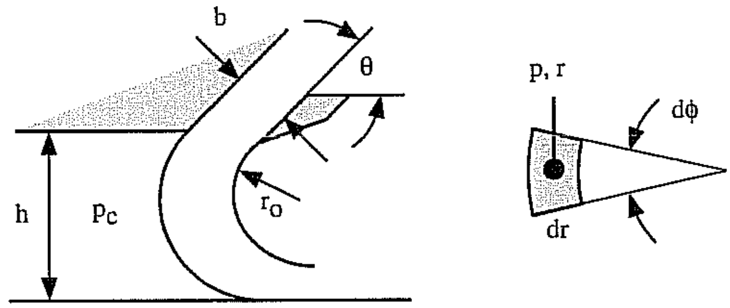


Figure 3 Thick jet model

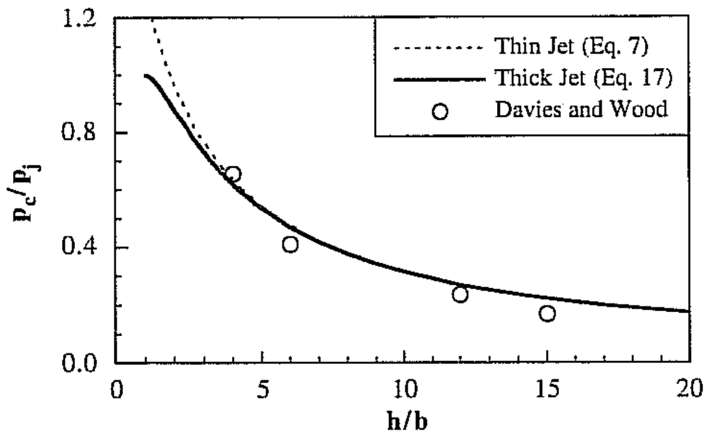


Figure 4 Comparison of theories and experiment for p_c/p_j

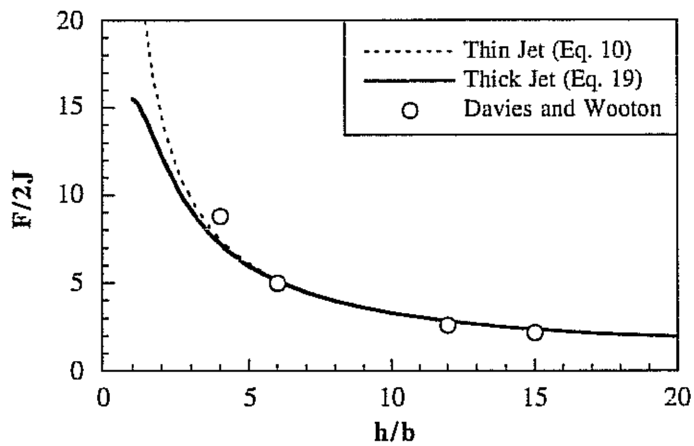
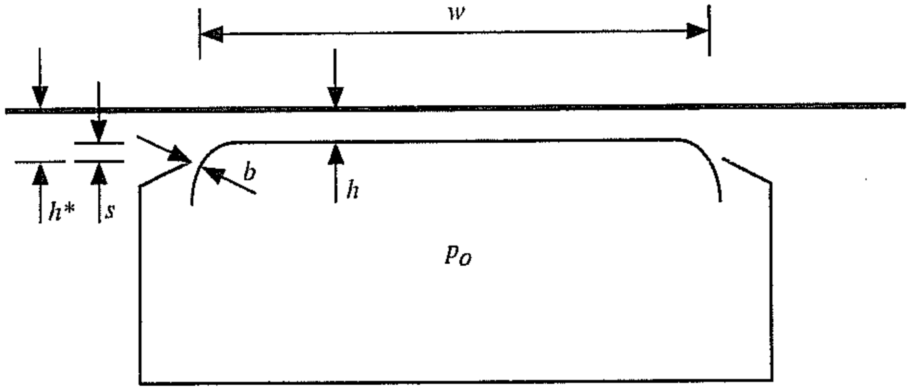


Figure 5 Comparison of theories and experiment for F/2J



Air Bar 1: w = 89 mm (3.5"), b = 1.65 mm (0.065"), s = 3.81 mm (0.15")
Air Bar 2: w = 127 mm (5.0"), b = 3.30 mm (0.130"), s = 3.30 mm (0.13")

Figure 6 A schematic of air bar

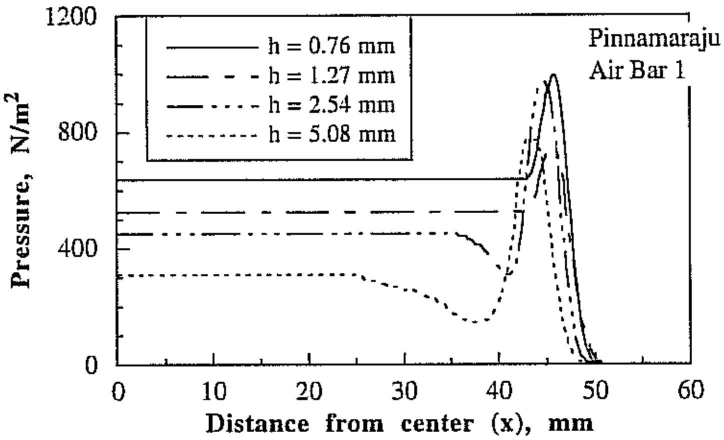


Figure 7 Effect of flotation height on the pressure distribution

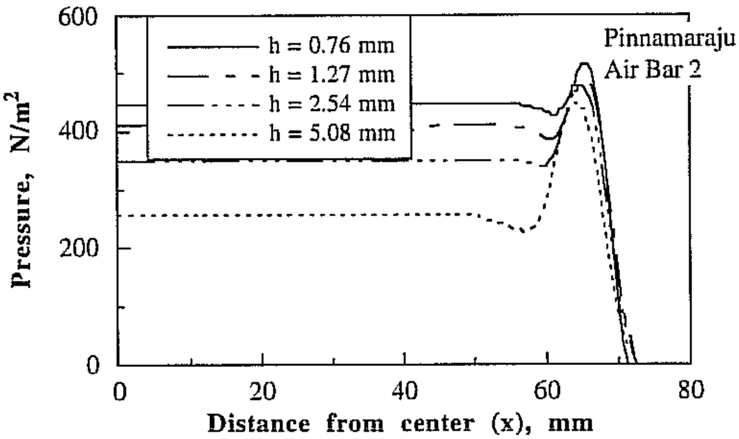


Figure 8 Effect of flotation height on the pressure distribution

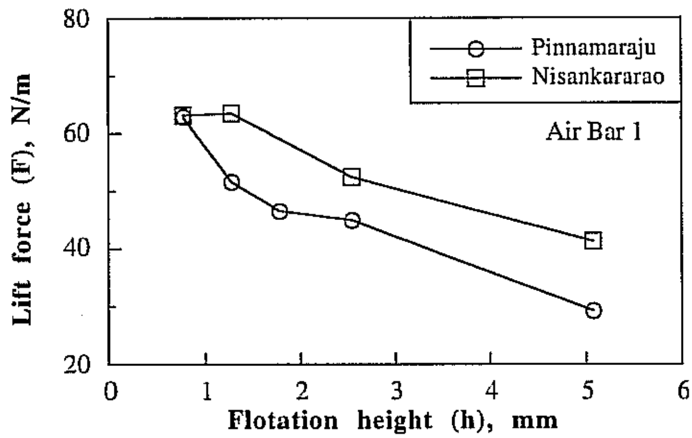


Figure 9 Effect of flotation height on the lift force

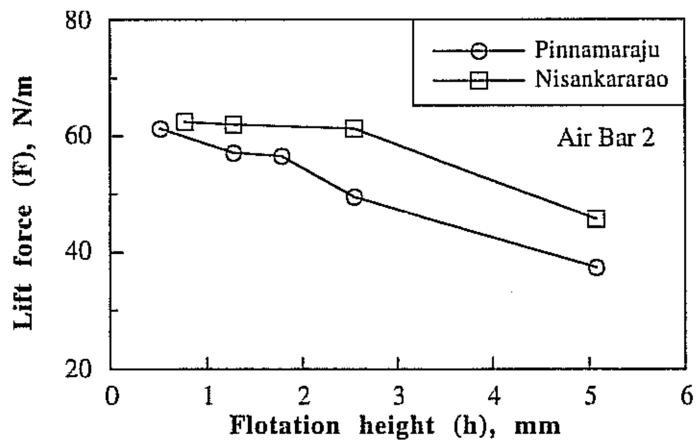


Figure 10 Effect of flotation height on the lift force

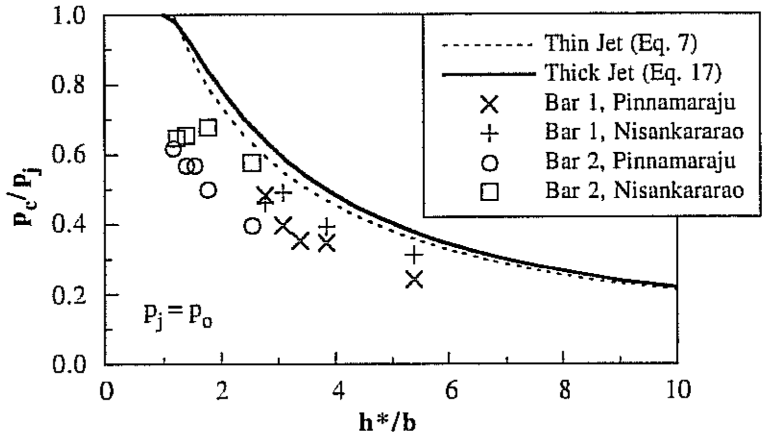


Figure 11 Comparison of theories and experiments for p_c/p_j

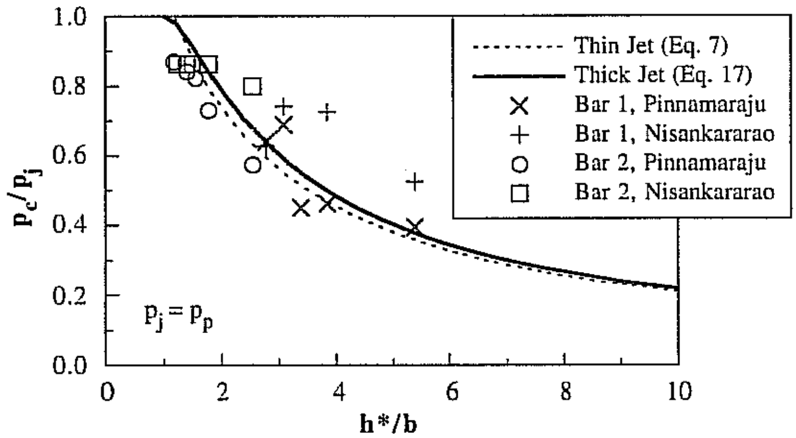


Figure 12 Comparison of theories and experiments for p_c/p_j

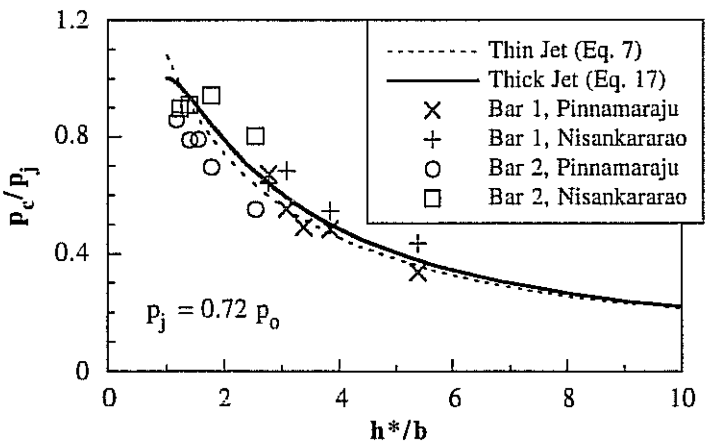


Figure 13 Comparison of theories and experiments for p_c/p_j

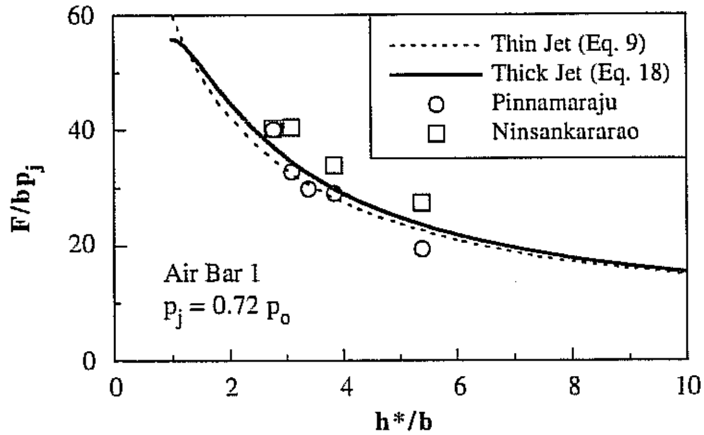


Figure 14 Comparison of theories and experiments for F/bp_j

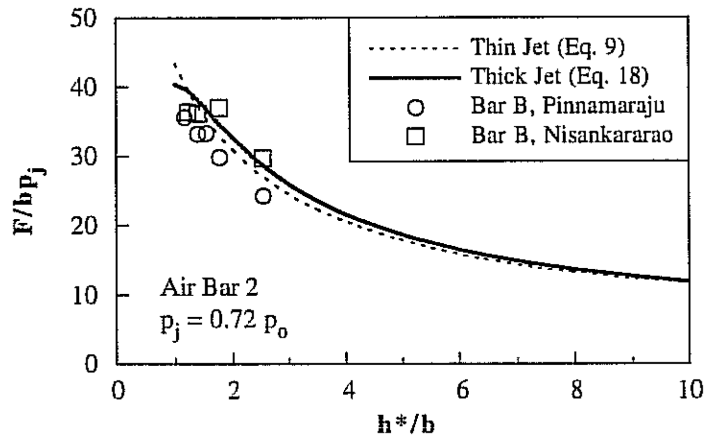


Figure 15 Comparison of theories and experiments for F/bp_j

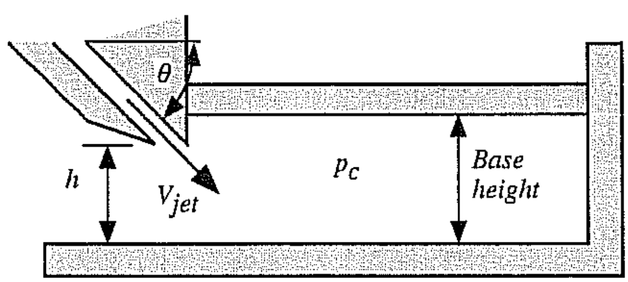


Figure 16 A schematic of Richardson's test model

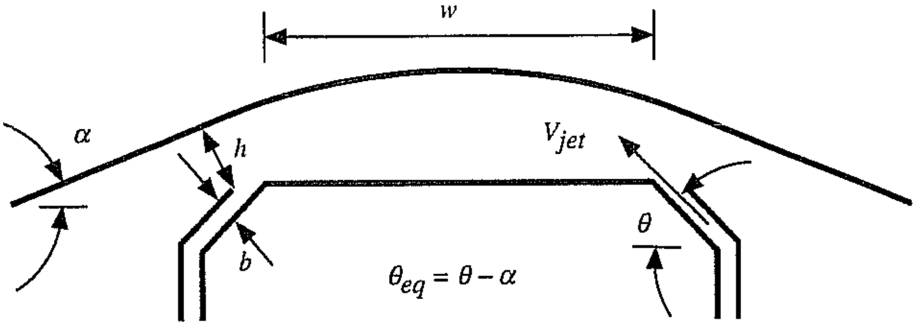


Figure 17 A flexible web supported by air bar

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Ground-Effect Theory and its Application to Air Flotation Devices
6/20/95 Session 5 9:00 - 9:25 a.m.

Question - Doesn't the angle theta depend on the pressure of the jet?

Answer - The measurement of the angle is very complicated and that's one thing we are not sure of. Possibly the angle depends the pressure of the air jet, which in turn is a function of the supply pressure. Unlike the classical ground-effect model which has a fixed position of flow separation, we see the Coanda effect in the tested air bars. Because we could not clearly define the angle of the air jet, we simply measured the position of the peak pressure (which is the position of reattachment) and by using the geometry of the nozzle we calculated the angle. The point of separation and the point of reattachment may be functions of the total pressure of the air jet and the cushion pressure.

Question - How much supply pressure did you use? How much variation was in the supply pressure?

Answer - For air bar 1 (b = 1.65 mm), the supply pressure was about 1300 Pa (0.19 psi); for air bar 2 (b = 3.3 mm), it was about 700 Pa (0.10 psi). We did not intend to change the supply pressure. However, the supply pressure changed a little depending on the gap between the plate the air bar. The variation was less than 10 % of the average values.

Question - Dr. Chang, I have two questions. First, you mentioned the Coanda effect. Quite a few air flotation bar manufacturers claim to use the Coanda effect to direct the flow essentially parallel to the moving web and sometimes to help transport it. Wouldn't the analysis be quite different for a moving web versus a stationary web or plate and also for a nozzle that utilizes the Coanda effect? Both of these would appear to affect the assumption of a circular shaped jet.

Question - My second question relates to the empirical nature of the constant applied to the test results. If I understand correctly, this constant was chosen to represent pressure drop through the particular design of bar and its value was chosen because it provided a good fit with theory. Does this mean that each design of air bar would need to be tested to determine the correct value for the correction constant?

Answer - For an air-foil bar, the Coanda effect is clearly observed all the time. For a pressure-pad type bar, however, the two opposing air jets cannot flow parallel to the web. Instead, each of the two jets must separate from the air bar surface near its exit and then move away from the air bar. Only when there is no web, the two opposing air jets follow the top surface of the air bar and then move away from the air bar near its center. Therefore, I believe that the assumptions for the basic ground-effect model are valid for the tested air bars. As I explained during the presentation, we need to study the effect of the curved surface of the air bar on the separation and reattachment of the air jet. Concerning the effect of a moving speed of the web, I think we can ignore it for most cases where the speed of the air jet is much higher than the speed of web. If there is any disturbance in the moving web which makes it tilt in the machine direction, the asymmetry of the two jets may cause problems as explained by Professor Moretti yesterday. Also, if the speed of web is very high, it is possible that the web can become unstable. Refer to [18] which discusses the possibility of breakdown of lift force at high speed motion of a hovercraft.

Answer - Yes. If the pressure loss at the nozzles is the major cause of error, as we assumed in this study, then we need to find the pressure loss coefficient for each air bar. The two air bars we tested show nearly the same value of loss coefficient, and it is possible that many of the air bars which have similar geometric properties have nearly the same loss coefficient. I think we need to study other possible reasons of error such as the side leakage flow (cross-machine-directional flow), and definitions of the departure angle of the jet and the flotation height for Coanda nozzles. Refer to [15] which shows that the ground effect theory overestimates the cushion pressure, especially when the Reynolds number is small and the ratio of flotation height to nozzle thickness is large.

Question - You have explained very clearly the situation at one single nozzle, but in practice there are a big number of these nozzles. And you explained the lateral forces. Have you done any investigation of the stability of a web when passing more than one air bar? This becomes a critical situation in practice. That will start to swing in lateral positions.

Answer - Near the end of the presentation, I explained lateral instability of webs supported by many air bars in an oven, and that is what Dr. Shelton is working on. We can calculated the distribution of the lateral loading generated by a series of air bars as a function of many different variables. We depend on Professors John Shelton and Bruce Feiertag for that analysis.

Question - Are there any means to keep a web in the centerline of a machine? I am asking for means of like changing air velocity on one side to control the web to keep it on the centerline.

Answer - Some air bar manufacturers tried different profiles of air pressure. Also, there was an idea of controlling the tilt angle of air bars (in cross machine direction) to control lateral position of a web. But I do not know if there is any successful method.

Thank you.