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PREDICTION TECHNIQUES FOR JET-INDUCED EFFECTS IN HOVER ON STOVL AIRCRAFT

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SUMMARY

Prediction techniques for jet-induced lift effects during hover are available, relatively easy to use, and produce adequate results for preliminary design work. Although deficiencies of the current method were found, it is still currently the best way to estimate jet-induced lift effects short of using computational fluid dynamics. Its use is summarized in this report. There is still much work that needs to be done to understand and predict jet-induced lift (suckdown), some of which is in progress.

The "new" method also summarized in this report, represents the first step toward the use of surface pressure data in an empirical method, as opposed to just balance data in the current method, for calculating jet-induced effects. Although the new method is currently limited to flat plate configurations having two circular jets of equal thrust, it has the potential of more accurately predicting jet-induced effects including a means for estimating the pitching moment in hover. As this method was developed from a very limited amount of data, broader applications of this method require the inclusion of new data on additional configurations. However, within this small data base, the new method does a better job in predicting jet-induced effects in hover than the current method. Studies are currently underway to expand the jet-induced suckdown data base in general and it is hoped to increase both the understanding and the prediction accuracy of jet-induced effects in and out of ground effect in hover.

SYMBOLS

A_j total jet area

C_p pressure coefficient

d individual jet diameter

d_e equivalent jet diameter

f_l fountain increase factor at greater heights utilizing lift improvement devices (LIDs)

f_2 fountain increase factor at lesser heights utilizing LIDs

h nozzle height above the ground

k a factor

NPR nozzle pressure ratio

S planform area

T thrust

X distance from the moment reference point

ΔL jet-induced lift loss

ΔM jet-induced pitching moment

Subscripts:

base the value on the model lower surface to which the pressure distribution will asymptote as distance from the jet(s) is increased

f fountain

L lift improvement devices (LIDs)

m moment

max maximum

s entrainment, multi-jet.

sj entrainment, single jet

s,f entrainment, front jet

s,r entrainment, rear jet

∞ out-of-ground effect

INTRODUCTION

As interest in STOVL aircraft has increased over the last decade, jet-induced lift loss has become a critical design issue. Work has shown that there is a need for new and more systematic testing of jet-induced lift loss (suckdown). The current jet-induced lift loss (or suckdown) prediction method of reference 1 was empirically derived from tests of numerous planform and nozzle configurations dating back to the 1950s and is intended only for preliminary design calculations. This method is primarily based upon round jets of equal thrust with varying planform geometry, nozzle spacing, nozzle pressure ratio (NPR), and planform to nozzle area. Most configurations tested had nozzle pressure ratios ranging from 1.15 to 2.08 (with most of the data between 1.5 and 2.08), and planform to jet area ratios from 4.25 to 165 with a mean around 80. Much of the jet-induced data measurements are balance data with a very limited amount of pressure data.

Most of the recent STOVL designs employ higher nozzle pressure ratios and planform to jet area ratios. Current tests have shown that some of the terms for the current method (ref. 1) are overpredicted, but cancel when added giving a good overall prediction. A "new" method which uses pressure data and balance data for predictions is being developed. The current prediction method for jet-induced effects in hover is summarized, the proposed "new" prediction scheme is summarized, and results from this "new" method are compared to those using the current method.

CURRENT PREDICTION METHOD

The current method was assembled by Kuhn (ref. 1). Most of the available data used in reference 1 were from tests which provided only balance data. Although balance data gives only the total lift loss or gain for the configuration, pieces making up the total lift loss could be estimated by using data from many planform and nozzle configurations. The flow field for the current prediction method was assumed to look like the one shown in figures 1a and 1b. The method thus assumes that the lift loss is made up of the following four terms (fig. 1c):

$$\left(\frac{\Delta L}{T}\right) = \left(\frac{\Delta L}{T}\right)_{\infty} + \left(\frac{\Delta L}{T}\right)_{sj} + \left(\frac{\Delta L}{T}\right)_{s} + \left(\frac{\Delta L}{T}\right)_{f}$$

where

$\left(\frac{\Delta L}{T}\right)_{\infty}$ = base lift loss out of ground effect

$\left(\frac{\Delta L}{T}\right)_{sj}$ = lift loss induced by a equivalent single jet

$\left(\frac{\Delta L}{T}\right)_{s}$ = additional lift loss induced by multiple jets

$\left(\frac{\Delta L}{T}\right)_f$ = lift increment from the fountain flow

As the total lift loss force was the only term obtained from each model, the individual terms that make up the total lift loss had to somehow be estimated. The out-of-ground effect (OGE) base lift loss term $(\Delta L/T)_\infty$ is the loss the configuration sees when far above the ground, or out-of-ground effect, and is based on work from references 2 and 3. This term can be directly measured.

The equivalent single-jet lift loss term $(\Delta L/T)_{sj}$ is based on Wyatt's work (ref. 4). Although this term can not be directly measured, the jets can be made into an "equivalent" single-jet. The suckdown can then be estimated from the method developed from tests of single jets in various planforms. It has since been found that the method will substantially overpredict the single-jet suckdown for jet pressure ratios greater than 2.0. Therefore, for jet pressure ratios above 2.0, the value of 2.0 should be used in estimating the single-jet suckdown.

This leaves the multijet $(\Delta L/T)_s$ and fountain $(\Delta L/T)_f$ terms to be determined. In reference 1 it was assumed that the total jet entrainment term could be estimated and from which the multijet suckdown and fountain lift terms could be calculated. To calculate the total multijet lift loss, reference 1 assumed that there is additional suckdown from the entrainment regions generated by the interactions of the jet flows; the flow on the ground, the flow in the fountain, and the flow on the lower surface of the model (fig. 2). The entrainment surfaces were then unfolded onto a flat surface for which the lift loss could be estimated by using the method for single-jet configurations (bottom of fig. 2). This estimate was then subtracted, along with the out-of-ground effect base lift loss term $(\Delta L/T)_\infty$, from the total lift loss to obtain the fountain increment for correlation with K.T. Yen's theory (ref. 5) in which some terms had to be experimentally determined .

The fountain increment, based for this method on Yen's theory (using the experimentally derived constants and exponents), along with $(\Delta L/T)_\infty$ and $(\Delta L/T)_{sj}$, could then be subtracted from the total lift loss to obtain the multijet lift loss increment $(\Delta L/T)_s$. This multijet increment is the lift loss incurred in addition to the equivalent single-jet lift loss for the given planform. This technique gave values that appeared reasonable and were used for the estimation method of reference 1. It is now known that this estimation procedure tends to overpredict both the multijet suckdown and fountain lift terms. However the method is still valid and useful for configurations that are in, or close to, those in the data base, as the overpredictions of the two terms tend to cancel and give the correct overall lift loss. Figure 3 shows a prediction for a three-jet flat plate model that was in excellent agreement with test data.

Lift Improvement Devices (LIDs) are important for many configurations as they can capture the fountain flow and significantly increase the positive fountain increment at low heights, thus decreasing the total lift loss. The current method for calculating the increase in fountain strength due to LIDs assumes the LIDs do not extend beyond the lines connecting the nozzle centers (figs. 4a,b) . LIDs can be of any shape inside this area with at most one open segment. The method will also account for jets located outside of the planform as shown at the bottom of figure 4b.

Examples using the current prediction method are shown in figures 5 to 7. Figures 5 and 6 show predictions compared to test data of two rectangular plates with different front to rear jet spacings.

These two figures also show the effects of LIDs on the total suckdown. Figure 7a shows the prediction for an AV-8B Harrier with and without LIDs. The LID increment factor trend is shown in figure 7b and is from reference 1. The LIDs for the Harrier are two longitudinal, nearly vertical, strakes formed from the gun pods. In hover, the plumes from the two front and two rear jets can be assumed to close the front and rear LID section to make a rectangular area. The predictions for the AV-8B were very good. Although the current lift loss prediction method will not predict jet-induced lift increments exactly, it does give a good indication of the lift losses expected and the heights at which suckdown may become troublesome. The method is relatively easy to use and is primarily intended for conceptual or preliminary design work.

PROPOSED NEW PREDICTION METHOD

Although the current method gave approximately the correct total suckdown, more recent tests (refs. 6, 7, and 8), have showed that both the fountain and multijet increments are over-estimated. It was thought that a more accurate method could be derived from tests that provided pressure data in addition to balance data. The tests described in references 7 and 9 (conducted at NASA Ames and Lockheed's Rye Canyon facility) provided most of the data to date, with some additional pressure data from references 6, 8, and 10. With this data in hand, R.E. Kuhn proposed a new prediction scheme (ref. 11). This new scheme will be referred to as the "new method." This new method is currently limited to flat plate configurations with two circular vertical jets of equal thrust.

Previous to the tests of references 6 and 7, it was assumed that the pressures induced on the outer regions of the planform (furthest from the jets and fountain) would asymptote to those induced by an equivalent single jet (fig. 1b). Further, it was assumed that the fountain lift could be obtained by integrating those pressures above the average level that would be induced by an equivalent single-jet as depicted at the top of figure 8. However, after examining the pressure profiles from reference 7, it was found that at the lower heights, the base Cp does not asymptote to that induced by an equivalent single-jet (bottom of fig. 8) as previously thought. At the lower heights, the base Cp was considerably less. Attempts by R.E. Kuhn to develop a simple way to relate the pressure at the edges of the planforms and away from the jets to the equivalent single-jet pressure were unsuccessful and it was decided to leave the suckdown increment due to an equivalent single-jet out of the method.

Thus the new method is currently made up of the base lift loss out-of-ground effect, the lift loss induced forward of the fountain region, the lift loss induced aft of the fountain region, and the fountain lift itself.

$$\left(\frac{\Delta L}{T}\right)_{\infty} = \text{base lift loss out of ground effect}$$

$$\left(\frac{\Delta L}{T}\right)_{s,f} = \text{lift loss induced forward of the fountain}$$

$$\left(\frac{\Delta L}{T}\right)_{s,r} = \text{lift loss induced aft of the fountain}$$

$$\left(\frac{\Delta L}{T}\right)_{f} = \text{lift increment from the fountain flow}$$

Thus,

$$\left(\frac{\Delta L}{T}\right) = \left(\frac{\Delta L}{T}\right)_{\infty} + \left(\frac{\Delta L}{T}\right)_{s,f} + \left(\frac{\Delta L}{T}\right)_{s,r} + \left(\frac{\Delta L}{T}\right)_{f}$$

The pitching moment is assumed to be the sum of the lift loss terms multiplied by their respective moment arms.

$$\left(\frac{\Delta M}{Td_e}\right) = \left(\frac{\Delta L}{T}\right)_{\infty}\left(\frac{X_{\infty}}{d_e}\right) + \left(\frac{\Delta L}{T}\right)_{s,f}\left(\frac{X_{s,f}}{d_e}\right) + \left(\frac{\Delta L}{T}\right)_{s,r}\left(\frac{X_{s,r}}{d_e}\right) + \left(\frac{\Delta L}{T}\right)_{f}\left(\frac{X_{f}}{d_e}\right)$$

Figure 9 shows the key terms of the previous two equations. The terms $(\Delta L/T)_{\infty}$ and $(\Delta L/T)_{f}$ are described below. More details of these terms can be found in reference 11. The OGE lift loss is assumed to act at the center of area for the configuration, thus X_{∞} is the distance from the center of the planform area to the moment reference point.

The OGE lift loss is similar to the current method (ref. 1), except that some of the exponents and multiplying factors have been modified. The lift loss term for this new method is defined as follows:

$$\left(\frac{\Delta L}{T}\right)_{\infty} = K_{\infty}\sqrt{\frac{S}{A_j}}\left(\frac{Spd}{d_e}\right)^{1.58}(NPR)^{-0.5}$$

where

$K_{\infty} = -0.00010$

for tests in open air or very large rooms.

The nozzle pressure ratio and K_{∞} terms have been modified from the method of reference 1. It should be noted that it was found from the tests described in reference 7 that the room size did have a significant effect on the OGE lift loss term. The smaller rooms indicated a larger K_{∞} was needed to match measurements--this is probably due to the observable recirculation within the room.

The front or rear suckdown increments ($(\Delta L/T)_{s,f}$ and $(\Delta L/T)_{s,r}$) are negative in value and are determined from the planform area forward and aft of the fountain region and the minimum pressures associated with these regions on the undersurface of the planform. This minimum pressure data can be empirically fit for the different heights and planforms tested (see ref. 11).

The width of the fountain region is defined as the width at which the pressure coefficient goes through zero aft of the front jet and forward of the rear jet (bottom of fig. 9). This width appears to be a function of the height to jet-spacing ratio up to a height of about 1.5 times the half spacing between the jets. At the greater heights, the pressures were so small that the fountain width could not be determined with any precision. The maximum pressure in the fountain region is also one of the terms used for predicting the fountain lift increment; thus far it too can be empirically fit. If the pressure in the fountain region was constant, the lift increment would simply be the fountain area multiplied by the pressure. In actuality (for the two jet configurations tested), the pressure peaks at the fountain center, drops off slightly toward the edge of the planform, and rapidly decreases to zero in the direction of the jets. In an attempt to identify how the maximum pressure in the fountain region could be related, if at all, to the actual fountain force, the actual fountain force (obtained by integrating the pressures over the fountain area) was plotted against the maximum fountain pressure times the fountain area; both terms are nondimensionalized by the total jet thrust. Surprisingly, it was found that a factor of 0.5 (fig. 10) works for each of the configurations tested in references 7 and 9. The form of the fountain equation is shown below.

$$\left(\frac{\Delta L}{T}\right)_f = K_f\left(\frac{DS}{2A_j}\right) C_{p,\,max}$$

The new method is also able to predict pitching moments in hover, while the current method (ref. 1) is not. As mentioned earlier, the hover pitching moments for the new method are calculated by multiplying the lift increment terms by their respective moment arms. At the higher heights (approaching OGE), the effective arms of the suckdown terms approach the distance from the moment reference point to the center of area aft or forward of the moment reference point. As the height decreased, the suckdown and moment both increase, but at different rates, and the effective moment arm is decreased as shown in figure 11. The factor $K_{m,s}$ (again in fig. 11) attempts to account for this reduction of the effective moment arm. This trend was expected since the pressure distribution tends to peak under the vortex-like flows which occur between the fountain and each jet.

COMPARISON OF CURRENT AND NEW METHODS

As can be seen from figure 12, both the current and the new method successfully predict the total suckdown for the delta wing configuration of reference 7. However it can also be seen that the current method overpredicts both the multijet suckdown and the fountain lift. As mentioned earlier, these overpredictions tend to cancel and the total suckdown is predicted well as long as the configuration is within the data base of the current method (ref. 1).

If on the other hand, pitching moments are to be predicted, the lift loss increments need to be more accurate as each piece has its own moment arm. Errors in these values will not cancel as the fountain moment arm is normally much smaller than that of the multijet suckdown. Also, locations at which the various increments act are not defined for the current method of reference 1. The new method provides a means for predicting pitching moments while in hover. Figure 13 shows the moment breakdown for the delta wing configuration of reference 7. It can be seen that the new method predicts the pitching moments at the lower heights fairly well, but overpredicts when approaching the higher heights.

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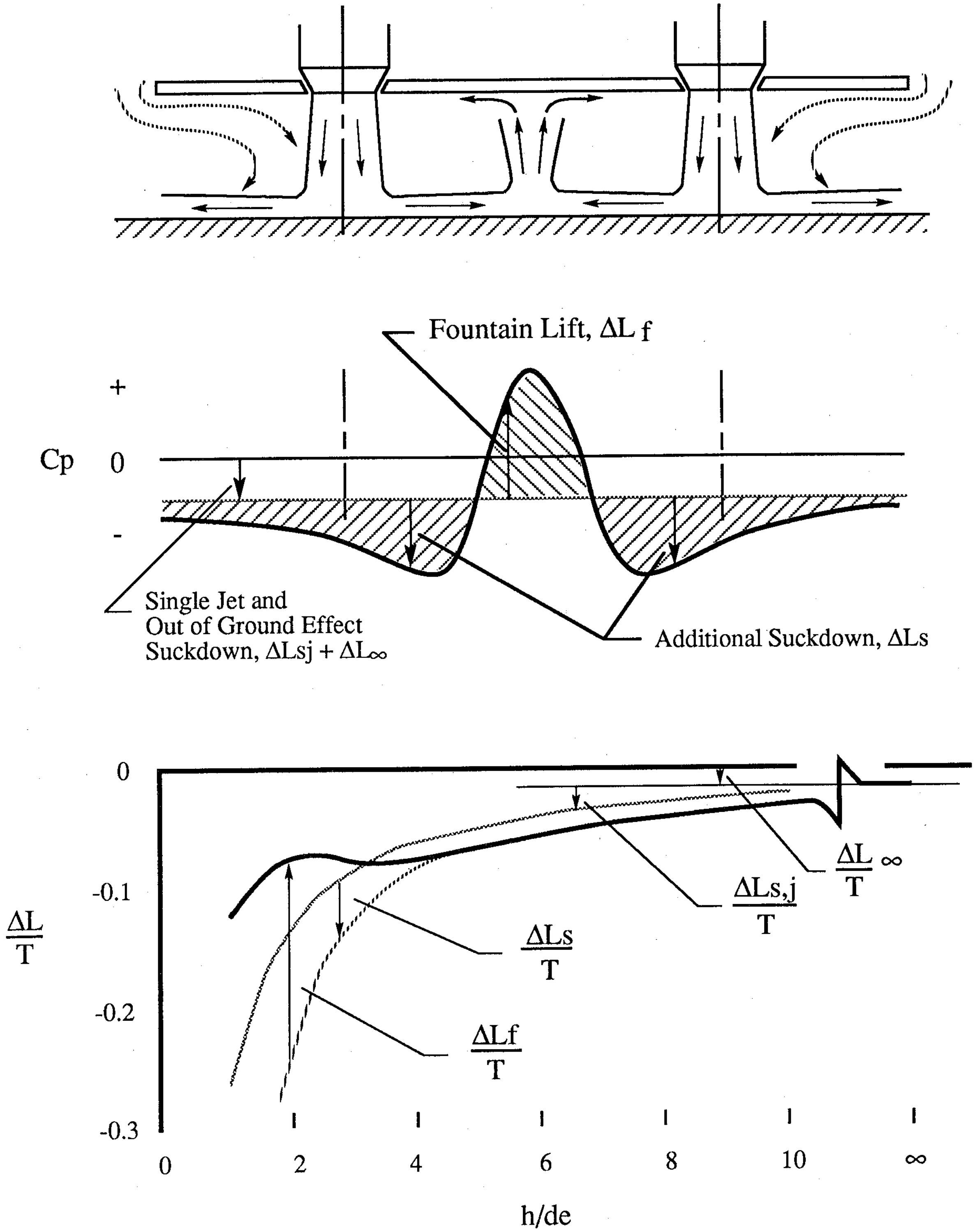


Figure 1. Jet-induced lift loss increments. Method of reference 1.

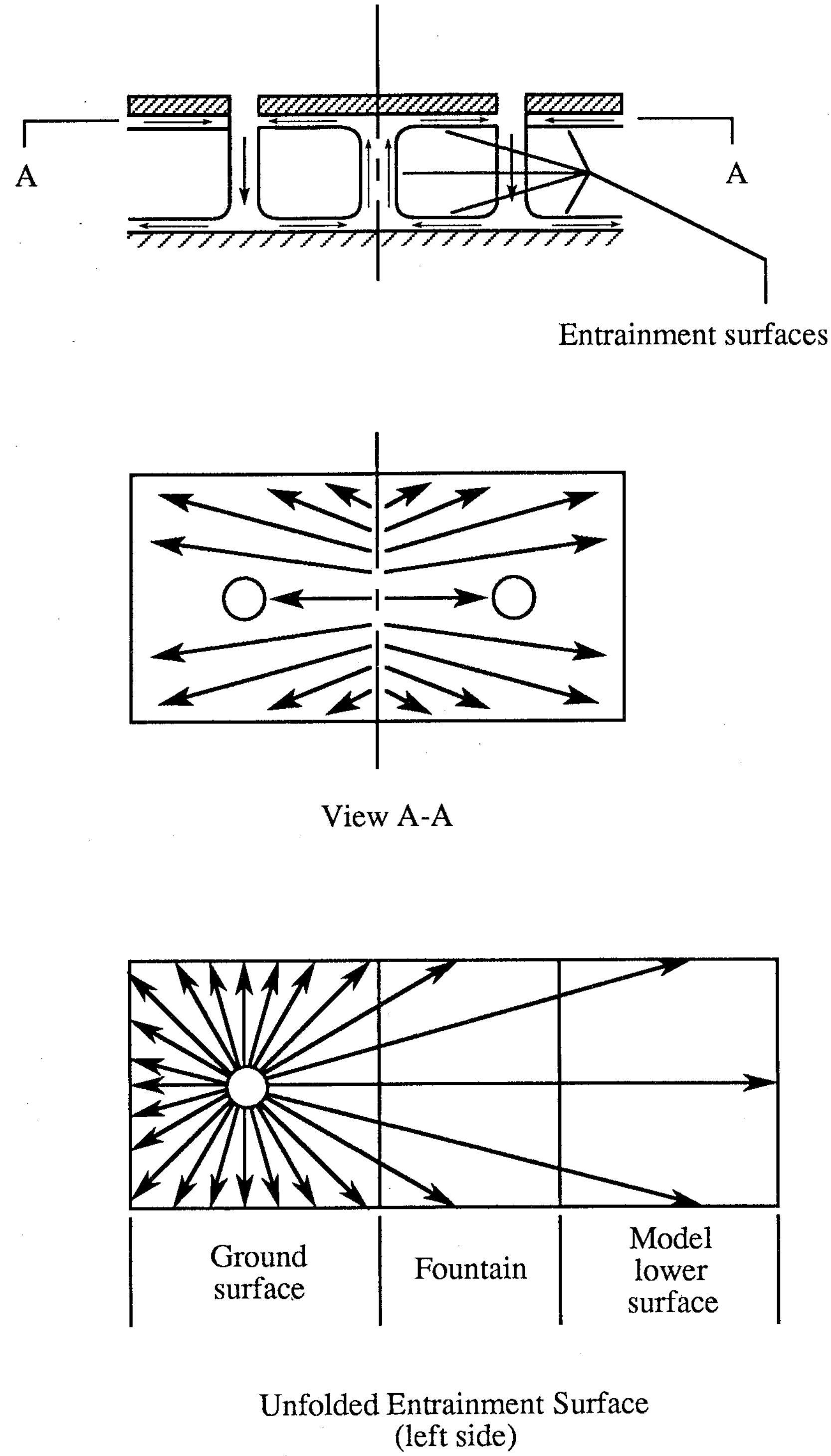


Figure 2. Entrainment surfaces for estimating multi-jet suckdown.

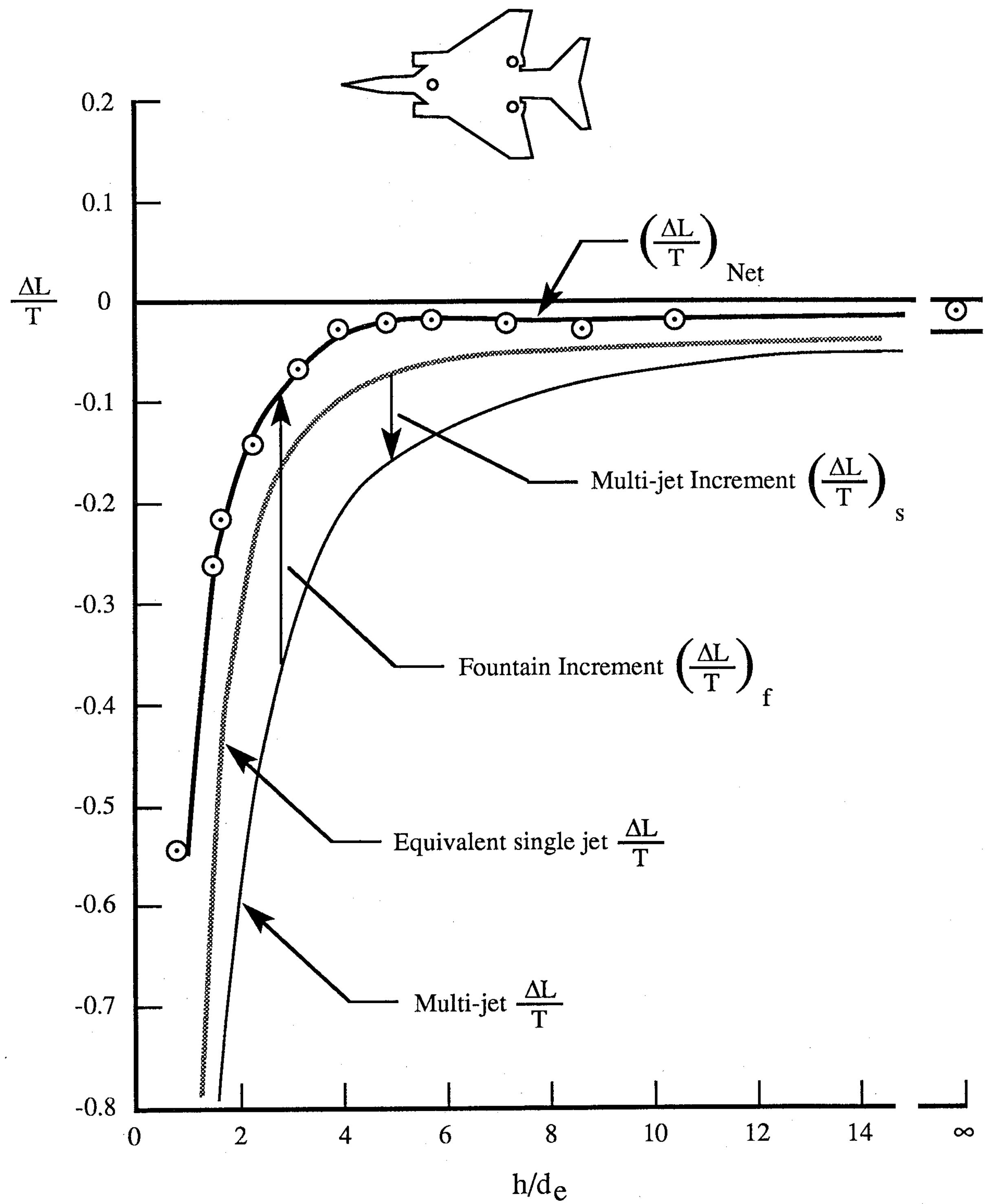


Figure 3. Example using a three jet configuration. Configuration 20 of reference 12.

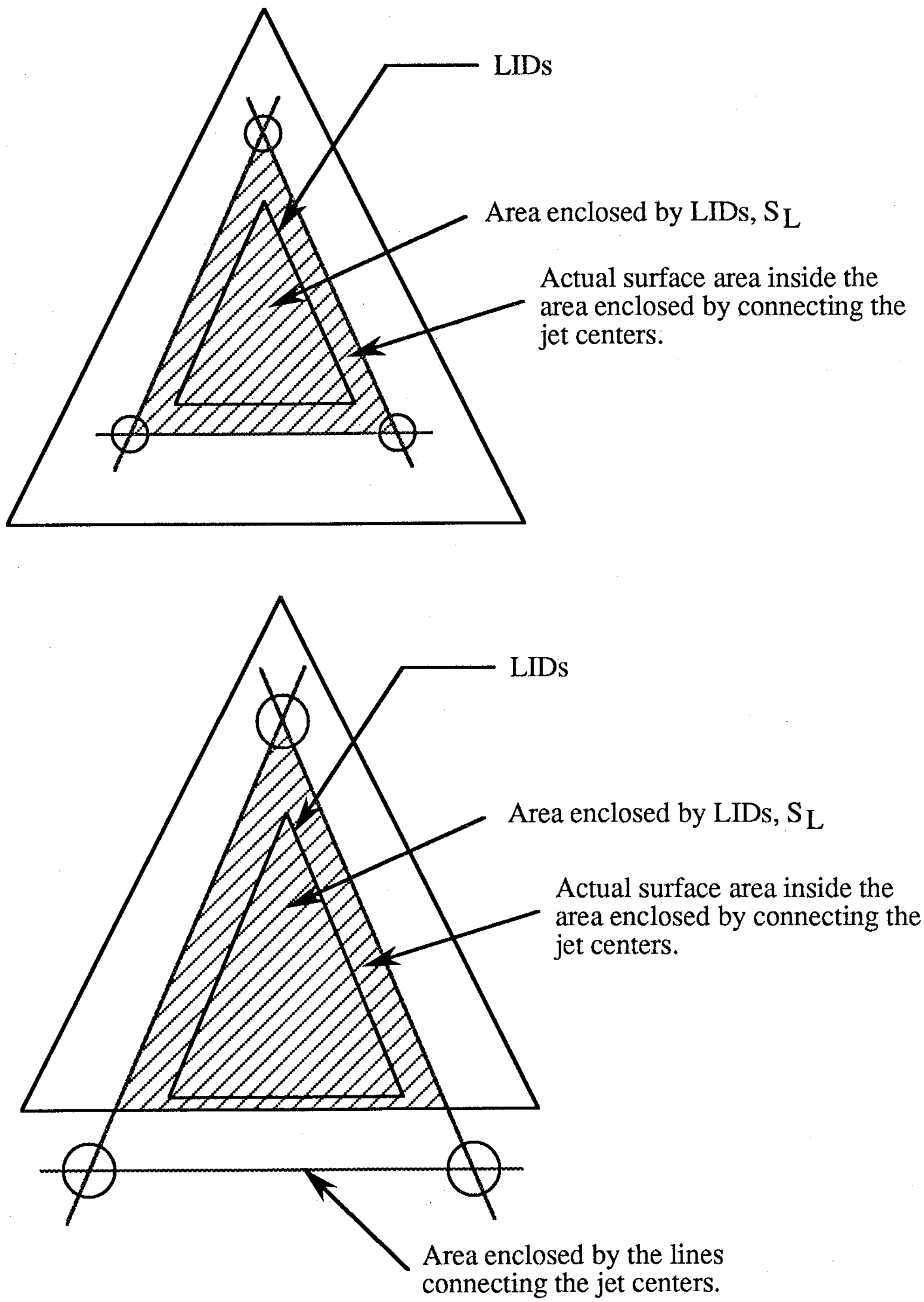


Figure 4. Lift Improvement Devices (LIDs).

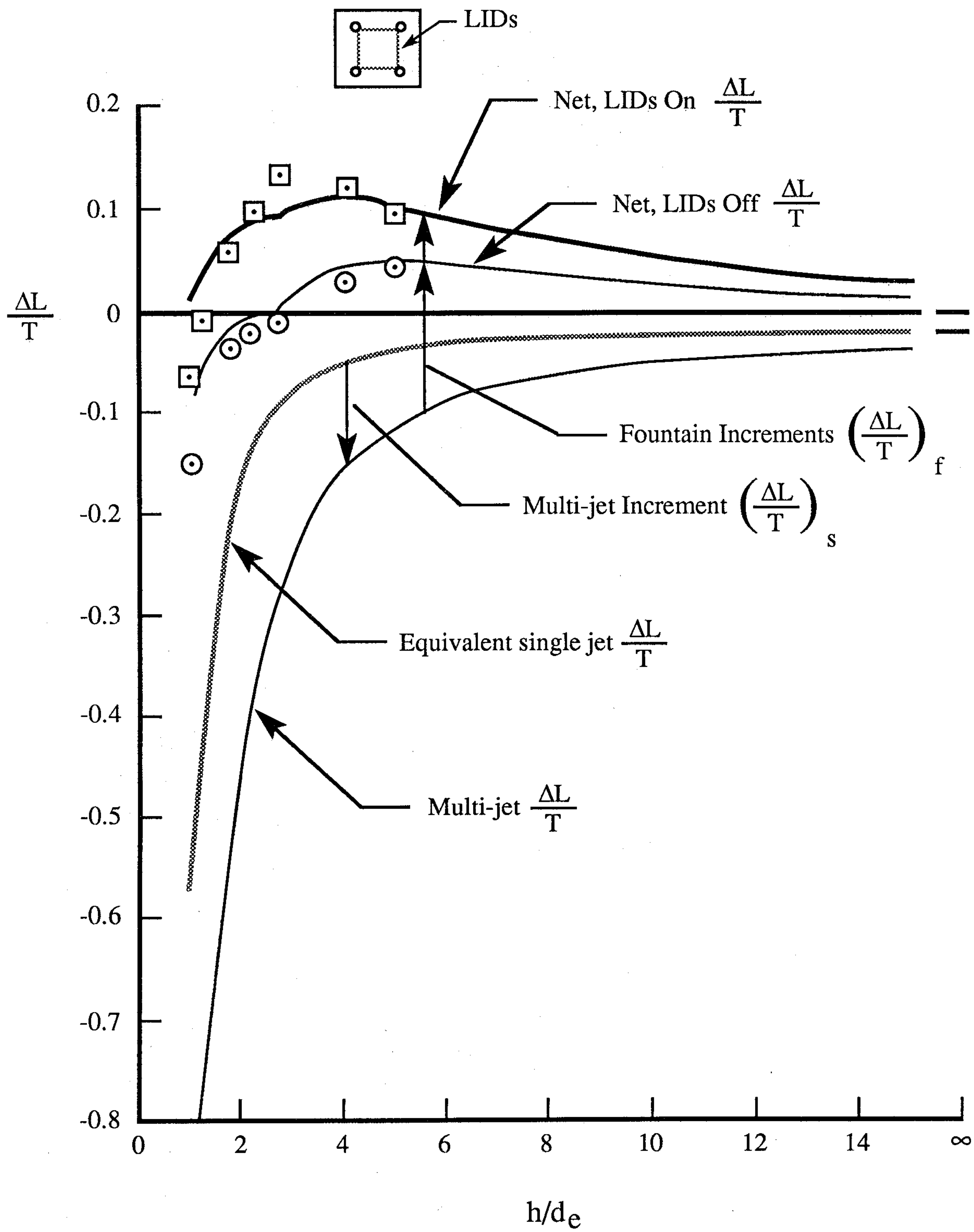


Figure 5. Example using a rectangular plate and close front to rear nozzle spacing (reference 1).

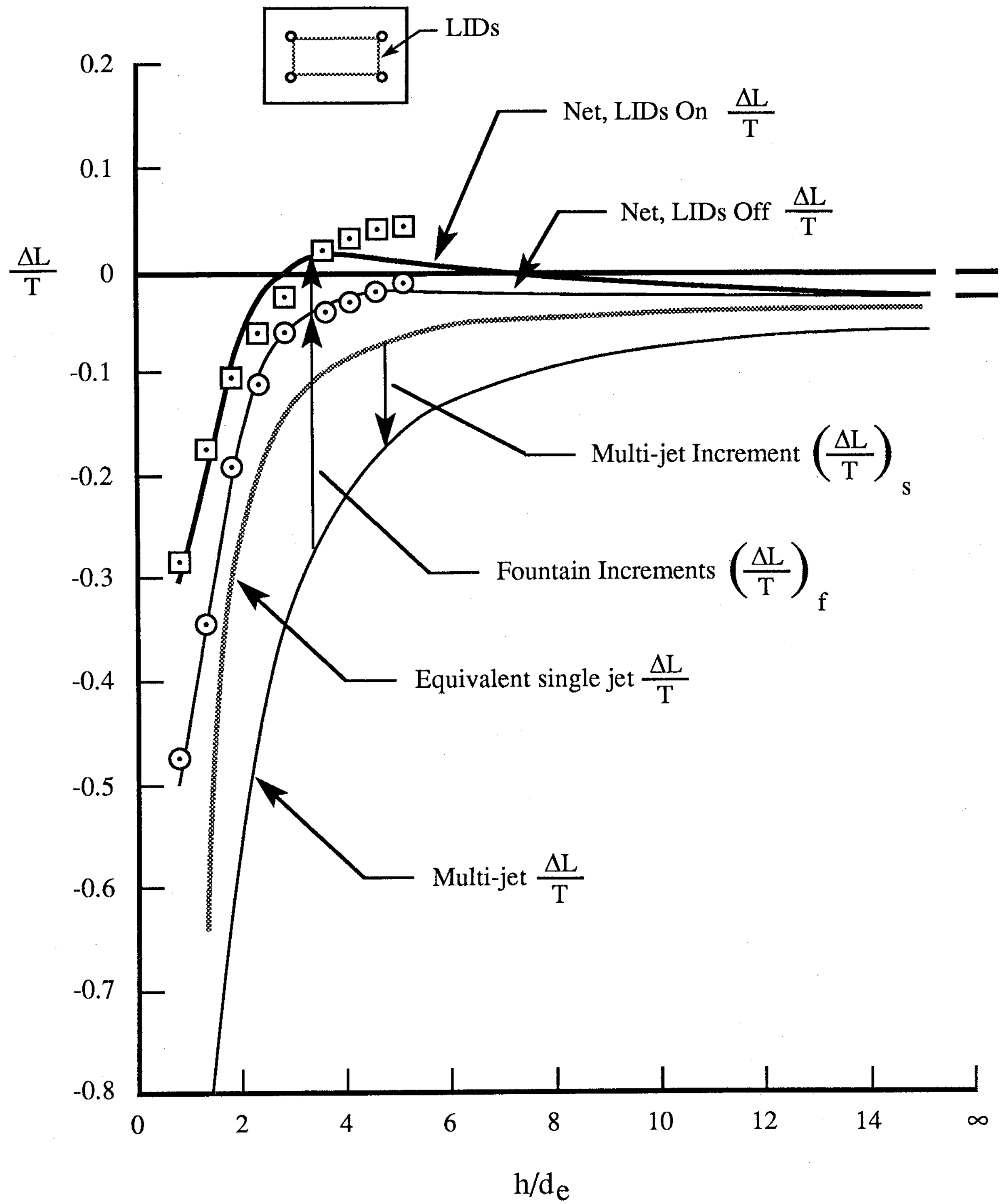


Figure 6. Example using a rectangular plate and large front to rear nozzle spacing (reference 1).

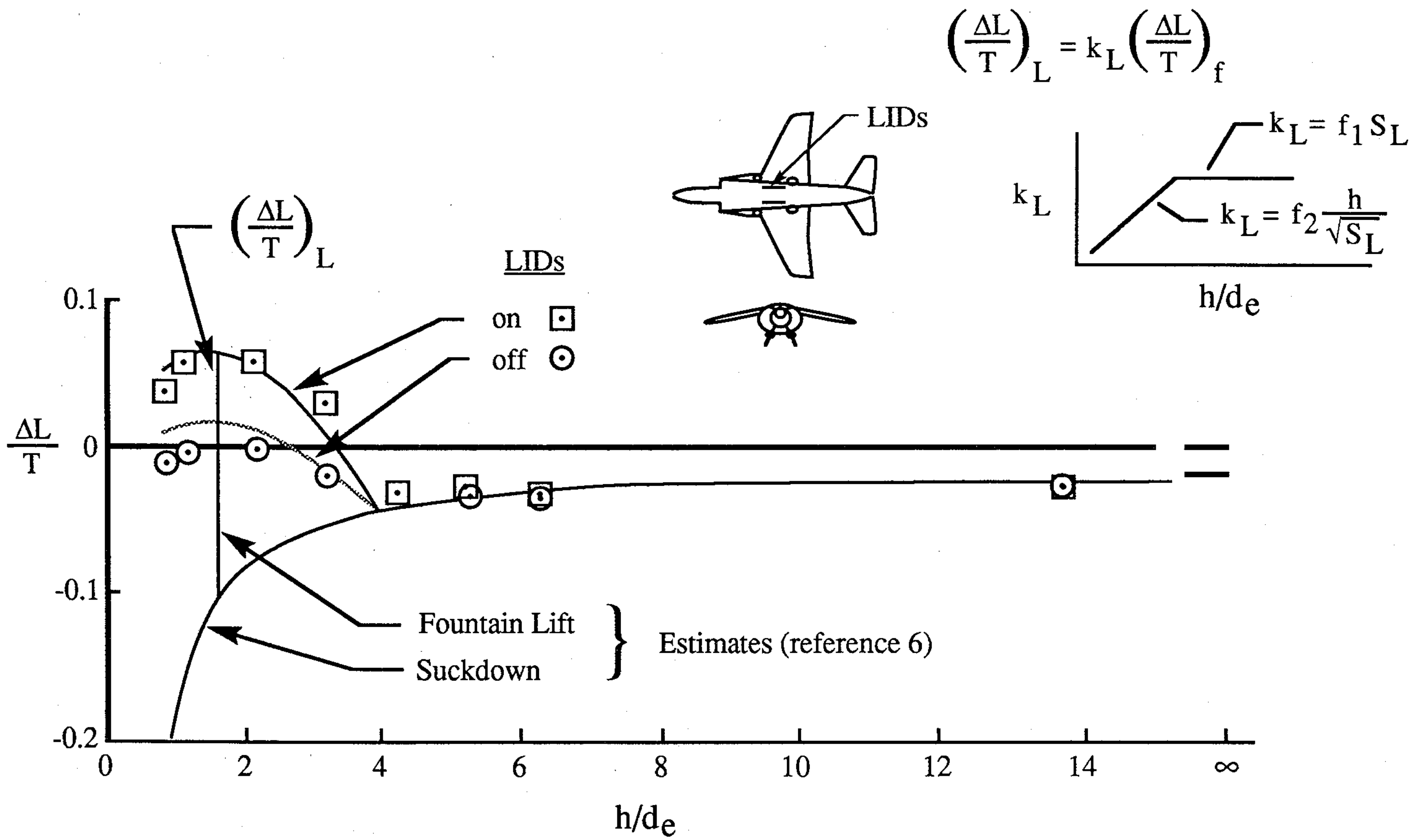
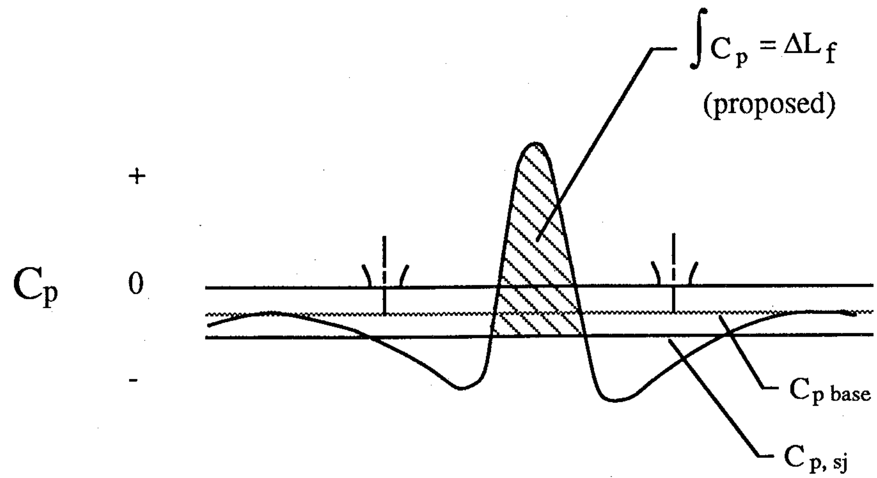


Figure 7. Lift induced on Harrier configuration hovering in ground effect (reference 12).



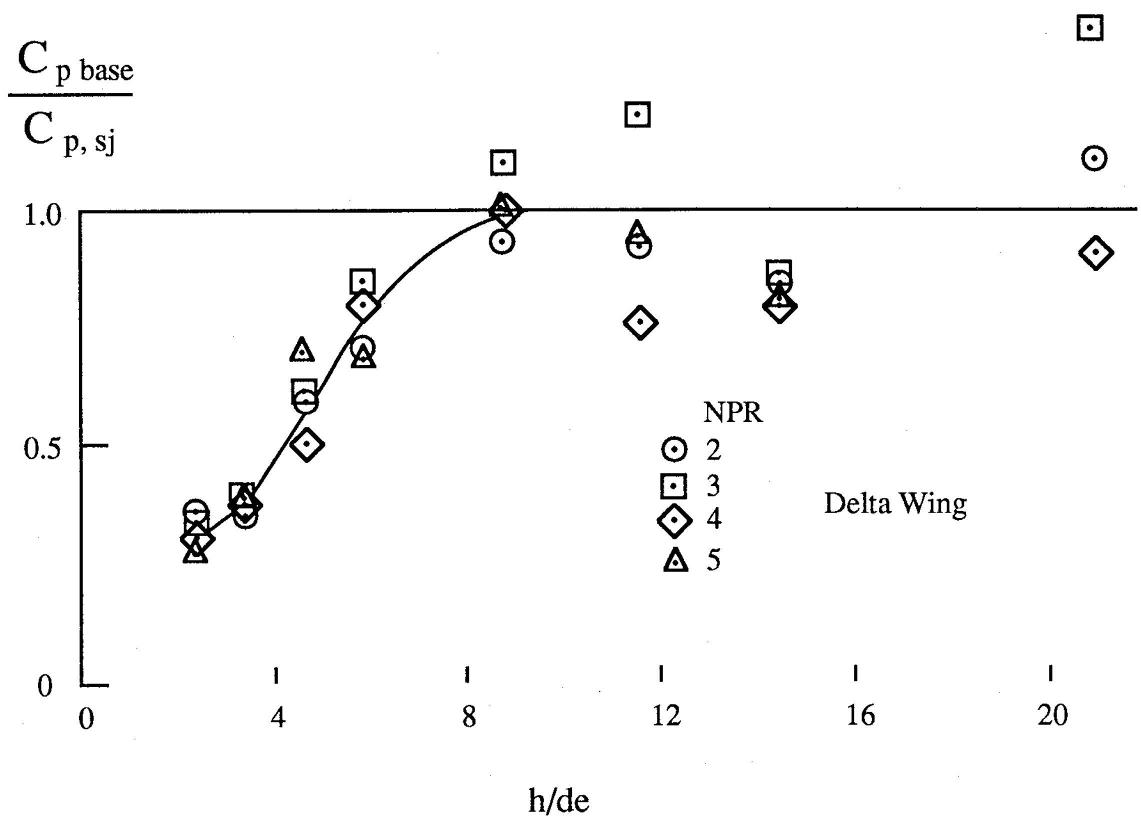


Figure 8. Relation of the pressures induced at the model edges to the pressures estimated for an equivalent single jet. Delta wing configuration of reference 7.

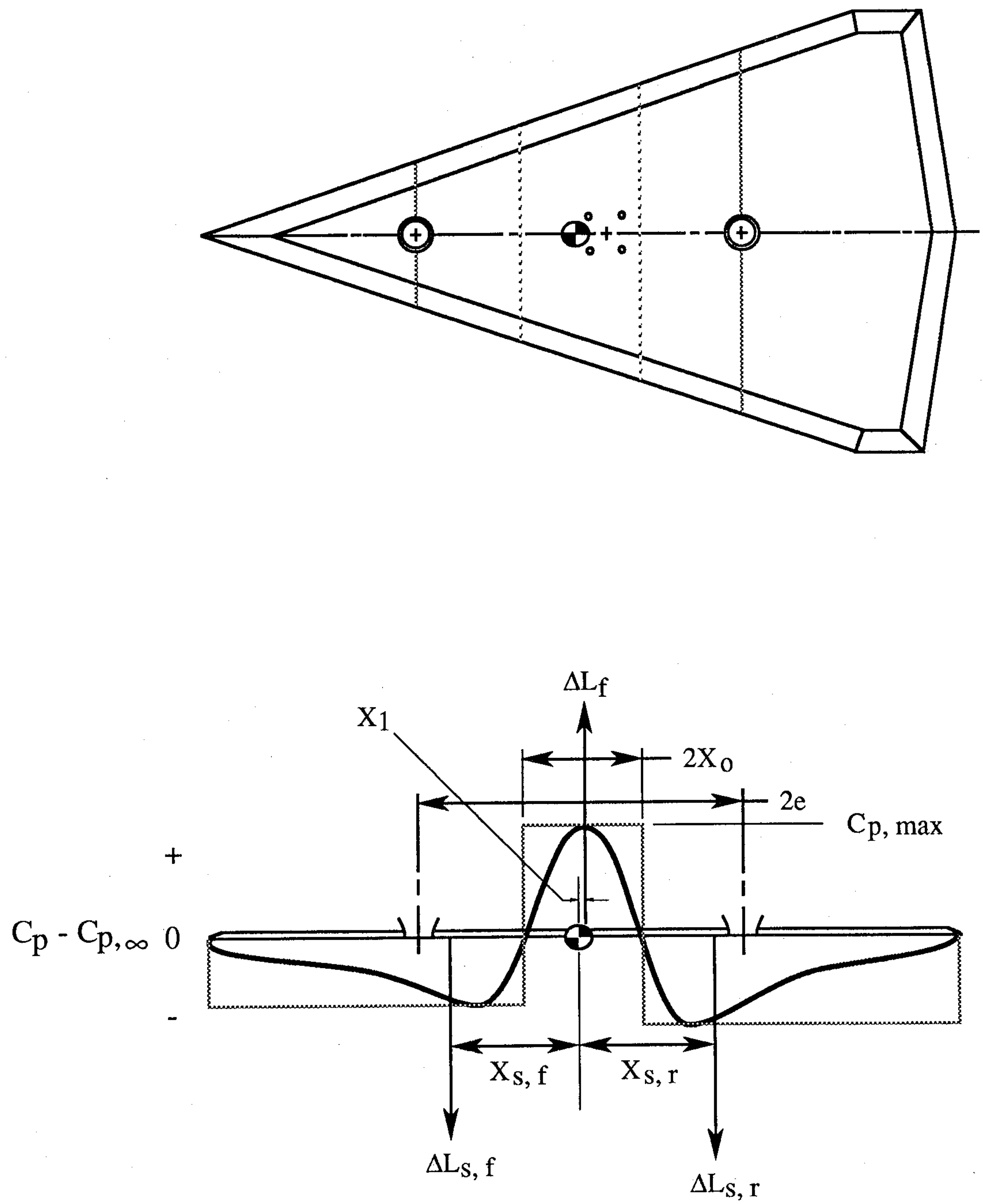


Figure 9. Presentation of new method (reference 11).

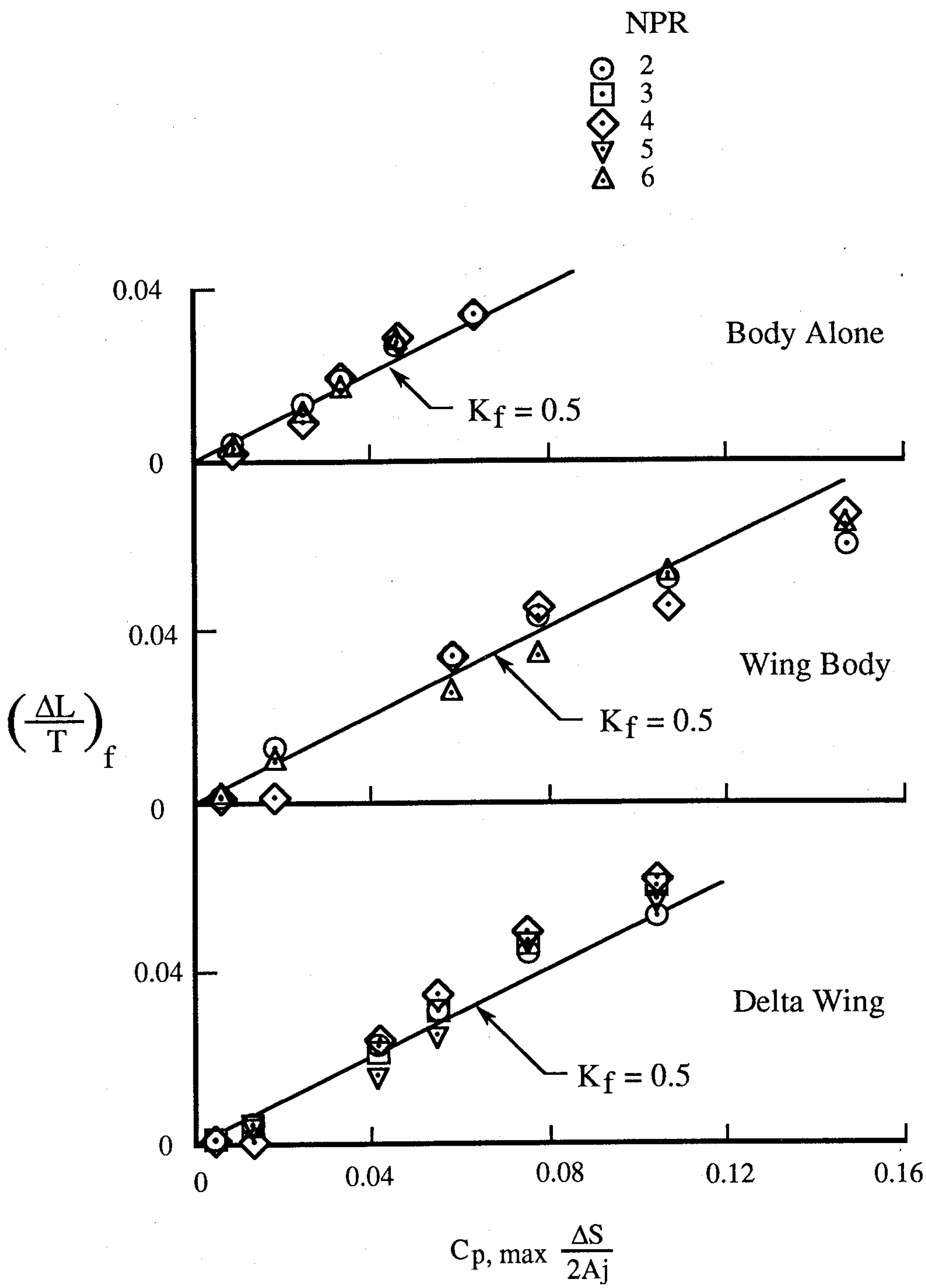


Figure 10. Evaluation of the fountain factor, K_f. Configurations from reference 7.

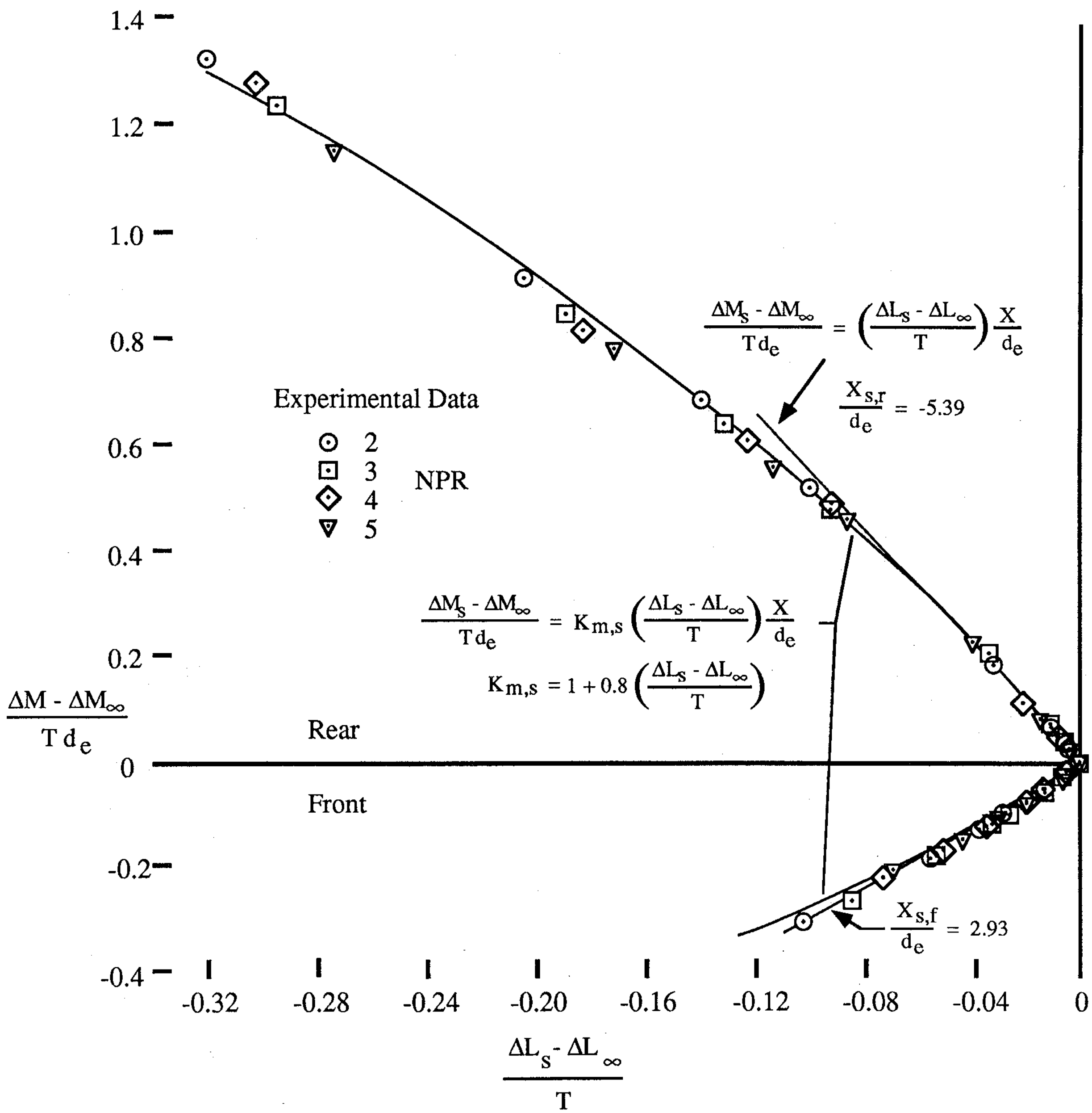


Figure 11. Correlation of pitching moment increments induced on forward and aft suckdown regions for the delta wing configuration of reference 7.

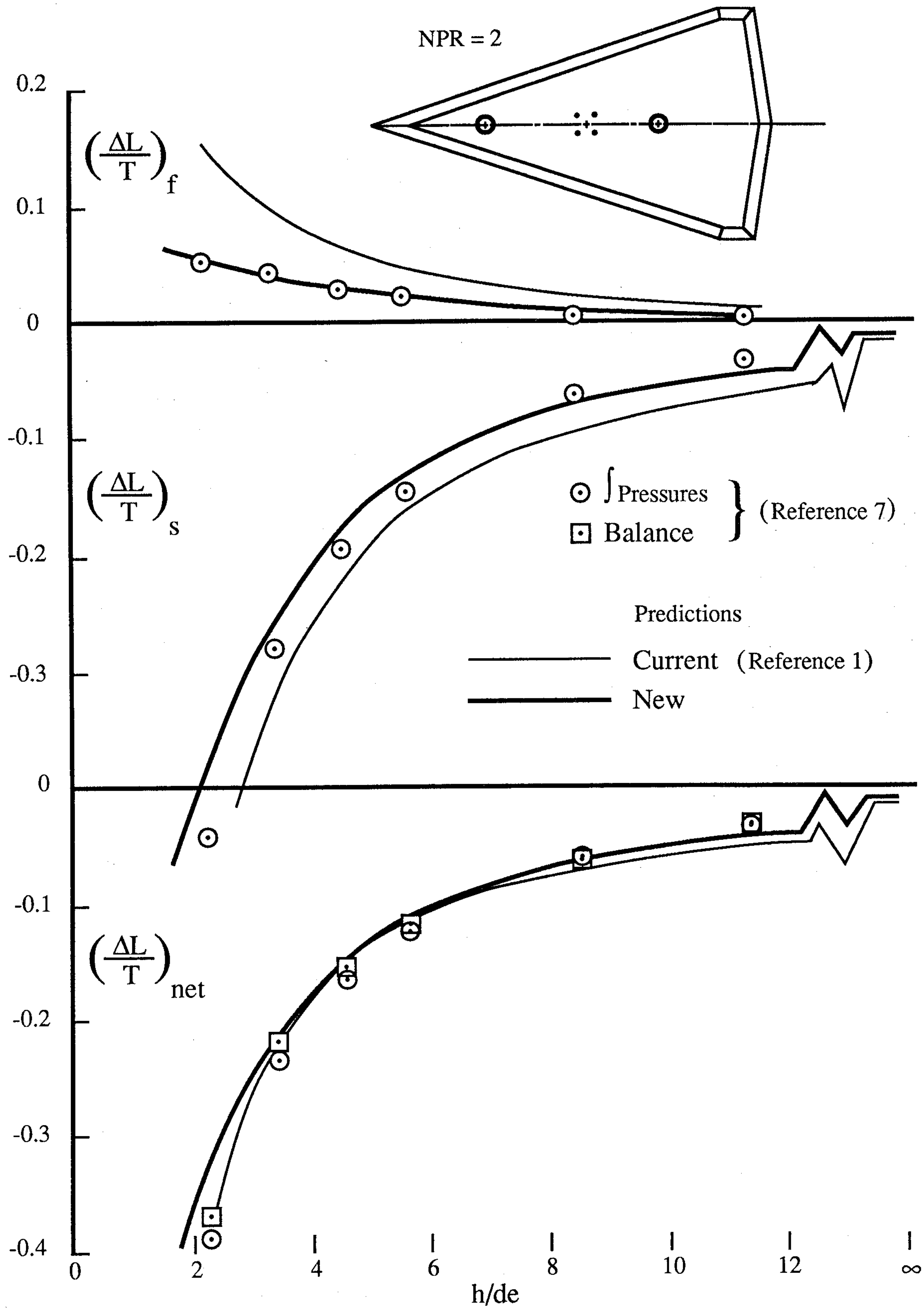


Figure 12 -- Lift loss comparison for the delta wing configuration of reference 7.

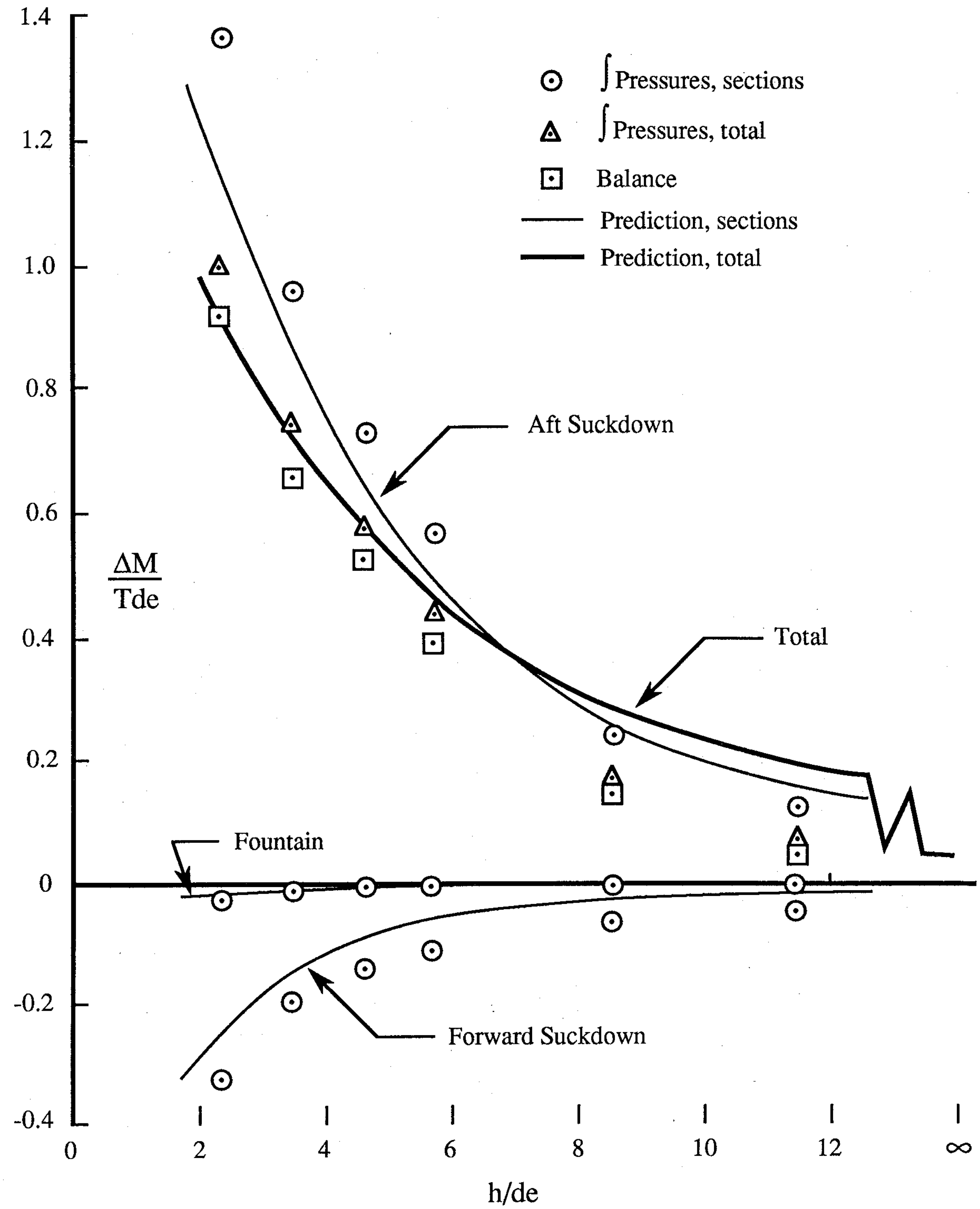


Figure 13 -- Pitching moment comparison for the delta wing configuration of reference 7.

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16. Abstract

Prediction techniques for jet-induced lift effects during hover are available, relatively easy to use, and produce adequate results for preliminary design work. Although deficiencies of the current method were found, it is still currently the best way to estimate jet-induced lift effects short of using computational fluid dynamics. Its use is summarized in this report. There is still much work that needs to be done to understand and predict jet-induced lift (suckdown), some of which is in progress.

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