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CONSIDERATIONS IN THE DESIGN OF TIP-COUPLED AIR-TRANSPORT SYSTEMS

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ABSTRACT

It is shown that the lift-drag ratio of tip-coupled systems can be expressed as a simple multiple of the lift-drag ratio of the isolated units comprising the system. When operated for maximum lift-drag ratio, the extent of the coupled system is limited by maximum lift coefficient, high-altitude engine characteristics, and degraded performance of the isolated unit climbing to couple into the system. When operated at constant altitude, the gain from coupling is severely limited. If the cruise altitude is that for best performance of the isolated unit, the system lift-drag ratio can be no better than twice that of the isolated unit even when an infinite number of units are coupled. System performance may be further degraded since span-load distributions which yield good performance for the individual units reduce the efficiency of the coupled system.

Coupling a pair of modern transport aircraft results in only about half the expected gain because of a poor span-distribution across the coupled pair. The control deflections required to maintain roll and pitch equilibrium further degrade the possible gain.

INTRODUCTION

One of the most obvious means of increasing the aerodynamic efficiency of an aircraft is to reduce the induced drag by means of an extremely large aspect ratio. Unfortunately, this procedure leads to large spans with attendent large wing weights. In addition, the large span tends to present many practical problems in ground handling, taxying, landing, and takeoff when using current airports. Possibly these difficulties could be overcome provided that the aircraft could land and take off as smaller modules and be assembled into a large-span cruise configuration in flight by coupling the modules at their wing tips. The small modules could be specifically designed for operation in an extended version of such a "sky train," or, conceivably, current aircraft could be coupled to provide improvements in either cruise efficiency or range.

The present paper provides a simple generic analysis of tip-coupled air-transport systems. The possibilities and problems of this type of operation are examined using a simple two-term drag polar to represent the aerodynamic performance of the individual modules. The analysis demonstrates that there are limitations on the improvement in efficiency and that the mode in which the system operates in cruise must be carefully considered to maximize the improvement. Next, the effect of the module planform (or span-load distribution) on the overall efficiency of the coupled system is considered. It is shown that simultaneous optimumization of the aerodynamic efficiencies of both the individual module and the tip-coupled system is not possible without the use of some form of variable wing geometry. Finally, the coupling of a pair of modern wide-body transports is considered and used to illustrate some of the required design considerations.

SYMBOLS

A	aspect ratio of wing, b^2/S
b	wing span
c	wing chord
C_D	drag coefficient, D/qS
$C_{D,o}$	profile drag coefficient, Do/qS
$C_{D,1}$	drag coefficient for lift-dependent portion of profile drag. (see eq. 16.)
C_L	lift coefficient, L/qS
C_ℓ	local lift-coefficient
D	drag
D_o	profile drag
e	airplane efficiency factor
$\bar{e}$	ratio of coupled efficiency factor to isolated efficiency factor
h	altitude
h_d	altitude at which isolated aircraft is designed to achieve maximum L/D
M	Mach number
m	ratio of operating lift coefficient to the optimum lift coefficient, $C_L/C_{L,opt}$

N	number of coupled units
q	dynamic pressure, $\frac{1}{2}\rho V^2$
S	wing area
V	aircraft velocity
y	lateral distance from centerline
Γ	circulation
λ	taper ratio, c_t/c_r
ρ	mass density of air

Subscripts

avg	average value
c	cruise value
max	maximum value
opt	optimum value
p	potential-theory value
r	root
t	tip

Primes denote that value is for the coupled system.

RESULTS AND DISCUSSION

Maximum Cruise Efficiency

For many preliminary design purposes, it is permissible to represent the drag polar of an aircraft by a simple parabola; that is,

$$C_D = C_{D,o} + \frac{C_L^2}{\pi A e} \qquad (1)$$

The efficiency factor e, introduced by Oswald in reference 1, includes the potential-flow efficiency of the wing, any interference drag, and the growth of parasite drag with lift coefficient.

Maximum range, or maximum cruise efficiency, is attained when the quantity ML/D is greatest. Since M is generally fixed by the onset of compressibility effects in modern transport aircraft, maximum efficiency will be essentially obtained under conditions where L/D is greatest. In consequence of equation (1), this ratio may be written as

$$\frac{L}{D} = \frac{C_L}{C_{D,o} + \frac{C_L^2}{\pi Ae}} \tag{2}$$

It is simple to show from equation (2) that the maximum value of L/D is attained at a lift coefficient of

$$C_{L,opt} = \sqrt{\pi Ae C_{D,o}} \tag{3}$$

Furthermore, the maximum value of L/D is

$$\left(\frac{L}{D}\right)_{max} = \sqrt{\frac{\pi}{4}\frac{Ae}{C_{D,o}}} \tag{4}$$

The Coupled System

At cruise altitude, the individual modules are coupled at the wing tips. Assume that all modules are identical and loaded equally. Further assume that the mutual interference between modules does not alter their profile drag. Then, it follows that

$$C'_L = \frac{NL}{qNS} = C_L \tag{5a}$$

$$C'_{D,o} = \frac{ND_o}{qNS} = C_{D_o} \tag{5b}$$

On the other hand, the aspect ratio of the coupled system is significantly altered. It becomes

$$A' = \frac{(Nb)^2}{NS} = NA \tag{6}$$

Operation at Maximum L/D

Coupled system.- After coupling, the assembled cruise configuration behaves as a single aircraft of increased aspect ratio. The maximum value of lift-drag is obtained by substituting equation (6) into equation (4), to obtain

$$\left(\frac{L}{D}\right)'_{max} = \frac{\pi}{4}\sqrt{\frac{A'e'}{C_{D,o}}} \tag{7}$$

Now, nondimensionalize equation (7) by dividing by the maximum lift-drag ratio of the isolated module as given by equation (4), to yield

$$\frac{(L/D)'_{max}}{(L/D)_{max}} = \sqrt{N\bar{e}} \tag{8}$$

Assuming for the moment that the efficiency factor e is unaltered by coupling ($\bar{e} = 1$), equation (8) shows that the maximum lift-drag ratio of the coupled system increases without bound as additional modules couple to the system (fig. 1). On the other hand, the cruise configuration must fly at ever increasing values of lift coefficient in order to attain its maximum lift-drag ratio. Performing the equivalent operations on equation (3) yields

$$\frac{C'_{L,opt}}{C_{L,opt}} = \sqrt{N\bar{e}} \tag{9}$$

Obviously, there is a maximum number of coupled units which can operate at maximum (L/D)' before the system stalls. This maximum number of units is obtained by setting $C'_{L,opt} = C_{Lmax}$ in equation (9) (see fig. 2) and solving for N to obtain

$$N_{max} = \frac{1}{\bar{e}}\left[\frac{C_{L,max}}{C_{L,opt}}\right]^2 \tag{10}$$

Furthermore, since the wing loading of the modules and the coupled system is unaltered by coupling, the lift-coefficient at which the coupled system operates can only be increased by either slowing down or by climbing to greater altitude. A lower cruise speed decreases the range factor ML/D and, simultaneously, decreases productivity to the point where it is not a viable alternative. Thus, the lift coefficient must be increased by flying higher to reduce ρ in indirect proportion to the increase in $C'_{L,opt}$. The actual required altitude depends upon the design altitude of the isolated module (that is, the altitude at which the individual module attains L/D_{max}). The required cruise altitudes are shown in figure 3.

The available thrust of turbine engines decreases rapidly at great altitudes, and, for a given engine, there is some maximum altitude above which it is impractical to operate. No attempt is made to determine such a limit herein; however, it is obvious from figure 3 that, whatever the engine limit is, it constrains the maximum number of modules that the system can contain and still operate at maximum efficiency. Figure 3 demonstrates that a decrease of about 3 km (10000 ft) in engine-limited altitude decreases the number of units by a factor of approximately two. Similarly, an increase of about 3 km (10000 ft) in h_d reduces the number of units by a factor of approximately three.

It is observed that a decrease in engine bypass-ratio tends to decrease the rate at which available thrust decreases with altitude. Thus, attempts to optimize the coupled cruise-system toward large numbers of modules may force the designer to choose lower bypass-ratio engines which inherently have greater specific fuel consumption.

Isolated module.- The performance of the isolated module must also be considered in the analysis. This module must climb from sea level to the cruise altitude of the coupled system. In some concepts, it must also be capable of transferring in flight from one "sky train" to another. Again assuming identical modules, equation (5a) shows that $C_L = C'_{L,opt}$ when the coupled system operates at maximum efficiency, and, in consequence of equations (3) and (6).

$$C'_{L,opt} = \sqrt{\pi N A e' C_{D,o}} \tag{11}$$

Now substitute equation (11) into equation (2) and divide by equation (4) to obtain

$$\frac{(L/D)}{(L/D)_{max}} = \frac{2\sqrt{N\bar{e}}}{1 + N\bar{e}} \tag{12}$$

Equation (12) demonstrates that the efficiency of the isolated module at coupling altitude decreases as a function of the number of coupled units (fig. 1). For four coupled units, the lift-drag ratio of the isolated unit is decreased by 20-percent; for 10 units, it is decreased in excess of 40-percent. The installed engine thrust must be increased by 25-percent in the first case, and by over 65-percent in the second case, if the module is to actually reach the altitude of the coupled cruise system.

Even when both the individual module and the coupled system operate at their respective optimum lift-coefficients, their lift-drag ratios differ significantly (eq (7)), and, consequently, there is a significant mismatch in required thrust between independent and coupled operation. Since the isolated unit operates at a lift coefficient significantly greater than $C_{L,opt}$ at coupling, this mismatch is further magnified. The resulting gross mismatch may add to development cost, production cost, and empty weight, and, in addition, may result in degraded specific fuel consumption during cruise.

Operation at Constant Altitude

Coupled system.- The preceding analysis indicates that operation of the coupled system at its maximum lift-drag ratio is not feasible under many circumstances; therefore, a simpler operational mode, at constant altitude, will be considered next. In the ensuing discussion, it will be convenient to specify the altitude indirectly in terms of the lift coefficient of the isolated module; that is

$$C_L = C_L' = mC_{L,opt} \tag{13}$$

The nondimensionalized lift-drag ratio of the coupled system of N units is obtained by substituting equations (6) and (13) into equation (2), and then dividing by equation (4), to obtain, after some simplification

$$\frac{(L/D)'}{(L/D)_{max}} = \frac{2mN\bar{e}}{N\bar{e} + m^2} \tag{14}$$

Equation (14) shows that the nondimensionalized lift-drag ratio approaches 2m as the number of units N approaches infinity. This is not inconsistent with equation (8) since, in the former case, the unbounded increase in (L/D)' was obtained only with an unbounded increase in C_L'.

Figure 4 shows equation (14) for the specific case of operation at the altitude which yields the greatest lift-drag ratio for the isolated module, and figure 5(a) shows the more general case where m can assume any arbitary value. The envelope of maximum lift-drag ratios in figure 5(a) is obviously the coupled-system curve of figure 1.

The bounded nature of the gain in (L/D)' with increasing N at constant altitude is obvious in figures 4 and 5(a) as well as in the mathematical limit of equation (14). Furthermore, as m (altitude) is increased, a greater number of units must be coupled to approach reasonably close to the limiting value of (L/D)'.

If the cruise altitude is high (large m), the efficiency of a small coupled system may be less than that of the individual modules flying near their best cruise altitude. For example, at an extreme altitude (m = 10), more than six coupled units are required to match the maximum lift-drag ratio of the isolated module. Under such conditions, it would be preferable to operate the modules independently at lower altitude.

Operation at constant altitude still entails compromises enforced by stall and by engine operating characteristics. The altitude (represented herein by m) must be chosen sufficiently small to avoid these limitations.

Isolated module.- The lift-drag ratio of the isolated module at cruise altitude is obtained by substituting equation (13) into equation (2) and dividing the resulting equation by equation (4) to yield

$$\frac{(L/D)}{(L/D)_{max}} = \frac{2m}{1 + m^2} \tag{15}$$

Equation (15) is shown in figure 5(b). It will be recognized as the generalized lift-drag ratio function of any aircraft which can be represented by a two-term drag polar (eq (1)). The greatest value of L/D occurs at $C_{L,opt}$ $(m = 1)$ and the efficiency decreases significantly for other lift coefficients.

If it is desired to avoid significant overpowering of the individual modules, these modules must operate reasonably close to $C_{L,opt}$. If m is chosen to be 1.5, the module must be overpowered by 10 percent and the maximum possible gain in the coupled system is an increase by a factor of three in (L/D)' as N approaches infinity. In a more practical sense, a factor of about two could be obtained with five units, or 2.5 with ten units.

Between the excess installed thrust for isolated operation and the reduction in required thrust for coupled operation, the individual modules must be significantly overpowered in cruising flight. This thrust reduction in cruise might allow shutting down some of the engines after coupling; however, this procedure is forbidden by current Federal Air Regulations.

Considerations in Module Design

Aspect ratio and profile drag coefficient.- The performance of the coupled system has been shown to relate directly to the performance of the isolated module irrespective of the aspect ratio or the profile drag coefficient. Thus, the best performance of the coupled system is obtained by optimizing the design of the individual module.

The requirements are simple; the module should have great L/D and, simultaneously, should have a small $C_{L,opt}$ to allow coupling a large number of units efficiently. Examination of equations (3) and (4) demonstrate that these requirements are satisfied simultaneously only by minimizing $C_{D,o}$. The profile drag must be as small as possible, but increases in aspect ratio tend to be self defeating in that increased aspect ratio also increases $C_{L,opt}$ which decreases the number of units that can be coupled efficiently. The use of laminar flow control should be particularly advantageous in a tip-coupled system since it offers the promise of a major decrease in friction drag.

Potential-flow efficiency factor.- One of the parameters determining the Oswald efficiency factor is the potential-flow efficiency of the wing. Normally, a wing is designed with a combination of twist, taper, and camber which produces an almost elliptic span-load distribution in cruise, thus minimizing the induced drag. The tip-coupled system presents a more complicated problem, for now the span-load distribution ideally should be elliptic in both the coupled and uncoupled modes of flight.

This problem has been examined in its simplest form by calculating the theoretical efficiency factors e_p for several module planforms of varying taper ratio using the North American Rockwell Unified Vortex Lattice (NARUVL) computer program (ref. 2). The efficiency factors have been obtained for the isolated module as well as for tip-coupled systems of as many as five identical units. The individual modules were assumed to have aspect ratios of 4.0 and module taper-ratios of 1.0, 0.5, and 0 were considered. In all cases, the wings were untwisted, untapered, and had zero leading-edge sweep. The planforms of these modules coupled into systems of five units are shown in figure 6.

The chosen planforms are qualitatively representative of three classes of wing span-load distribution. A rectangular planform (λ = 1.0) represents a heavier-than-elliptic loading near the wing extremities. With a taper ratio of 0.5, the span-load distribution is approximately elliptic. The pointed wing planform (λ = 0) has a less-than-elliptic loading toward the tips, sacrificing some aerodynamic efficiency in favor of reduced wing bending moments.

The calculated efficiency factors for the three planforms are shown as a function of the number of coupled units in figure 7. For a single unit, as anticipated, the planform with λ = 0.5 is the most efficient (by about 5 percent) since it most nearly approaches the ideal of elliptic span loading. For all planforms considered, the efficiency factor decreases as units are added, with the rate of decrease increasing as the taper ratio decreases. With only two coupled units, the rectangular (λ = 1.0) wing has become more efficient than the wing with a taper ratio of 0.5. The decrease is particularly rapid for the pointed wing (λ = 0), falling to values on the order of 0.3 by the time five units are coupled.

The radical changes in the potential efficiency factor imply that the ratio $\bar{e}$ in equations (8) to (14) is not a constant but that it decreases with N. Thus, the gains in efficiency from tip coupling are less than indicated in figures 1 to 5. Viewed in terms of an effective aspect ratio (fig. 8), the aspect ratio increases at a significantly reduced rate as N increased.

The reason for the loss in efficiency when coupled is clearly evident in the span-load distributions presented in figure 9. The differences in planform result in major variations in load distribution across the span of the coupled systems. Only the rectangular modules retain a span loading with a quasi-elliptic load distribution when coupled. In the extreme case of the pointed wing, the load drops to zero at each junction with a resulting aerodynamic performance that is more representative of formation flight than coupled flight.

The fact that the rectangular wing appears to be the best in figures 7 to 9 should not be taken as implying that an inverse taper (λ = 1) might be even better. If N becomes very large, the span-load distribution in the central portion of the coupled configuration will be approximately the same as for the normal (λ < 1) cases considered in figure 9. Thus, for large values of N, the potential-flow efficiency factor for modules of taper ratio $1/\lambda$ should be approximately the same as that for modules of taper ratio λ .

The concept of coupling modules to form a cruise system of vast aspect ratio depends upon approaching a two-dimensional case of zero induced drag as the coupled system is extended indefinitely. The only module planform which automatically satisfies this criterion is rectangular. In all other cases, the load distribution across the span does not approach uniformity as modules are added indefinitely. For each change in load (or circulation) over a span dy, the wing must shed a trailing vortex of strength $\frac{d\Gamma}{dy}$ dy. Thus, the cyclically repeating load distribution of the tapered modules results in a wake streamwise vorticity even for infinite aspect ratio and, consequently, the induced drag never approaches zero as in two dimensions.

In relation to the design of the isolated module, it is clear that a less than optimum load distribution must be adopted to avoid penalties when the system is coupled in the cruise mode. However, the performance of the coupled system is a relatively straight-forward ratio to the performance of the isolated module. Thus, the compromised span-load distribution of the module affects the performance of the overall system even when it is chosen so as to minimize the effect on the coupled system. One solution might be some form of variable geometry controlled automatically to adjust the spanwise load distribution according to the number of coupled units. Such a solution would add further complexity to a control system which would, in any event, be required to alter its characteristics to provide harmonized control in both the coupled and uncoupled modes.

Oswald efficiency factor.- The efficiency factors described in the preceding section do not correspond with the efficiency factor of equation (1), since, according to Oswald (ref. 1) that factor e must include all other lift-dependent drag such as interference and growth of profile drag with lift coefficient. Indeed, the proper value for e in equation (1) is likely to be on the order of 0.8 even when the potential-flow efficiency factor is close to 1 (ref. 3). The difference is largely caused by the restriction of equation (1) to a two term polar. In practice, the profile drag is not a constant, so that a more correct expression of equation (1) would be

$$C_D = C_{D,o} + C_{D,1}\,(C_L - C_{L,c})^2 + \frac{C_L^{\,2}}{\pi A e_p} \qquad (16)$$

Equation (16) and its subsequent treatment is basically similar to that given in reference 4 except for notation and the presence of $C_{L,c}$. The addition of $C_{L,c}$ is merely a recognition that a modern aircraft is designed with camber and wing incidence to produce minimum profile drag at a lift coefficient near that of cruising flight. Now equate equations (1) and (16) and solve for e, the equivalent Oswald efficiency factor, to obtain

$$e = \frac{e_p}{1 + \pi A e_p\, C_{D,1}\left(1 - \frac{C_{L,c}}{C_L}\right)^2} \qquad (17)$$

Equation (17) shows that the Oswald efficiency factor is equivalent to the potential-flow efficiency factor at only one value of C_L, namely $C_{L,c}$. For any other lift coefficient, e is less than e_p. Furthermore, at these off-design lift coefficients, the difference between e and e_p becomes greater as the aspect ratio increases. In the case of the tip-coupled system, which must operate at greatly different lift coefficients to obtain maximum L/D as units are added, this effect can be a severe penalty. The overall effect on efficiency may be significantly greater than illustrated in figures 7 and 8.

The use of equation (17) as a definition for e in equation (1) would considerably complicate the expressions for $C_{L,opt}$ (eq (3)) and $(L/D)_{max}$ (eq (4)) since equation (17) contains an additional term containing C_L. This procedure has been omitted herein since it is believed that the current simple equations adequately express the gross characteristics of tip-coupled systems in general.

Tip Coupling of Current Aircraft

Efficiency Factor.- A more modest scheme than developing specialized modules might be to couple two available aircraft at their tips so as to exploit the reduction in induced drag for either increased range or reduced fuel consumption. This prospect is examined herein by calculating the potential-flow efficiency factors and span load distributions of a current wide-body transport aircraft flying alone and flying coupled to an identical aircraft. The planforms of the single aircraft and the coupled pair are shown in figure 10. The calculations using the NARUVL program (ref. 2) included the camber, twist, and dihedral of the actual aircraft with the aeroelastic deformations expected in normal cruising flight.

Since the wing is cambered and twisted, the efficiency factors (fig. 11) become a function of the lift coefficient. At any lift coefficient, the efficiency of the coupled pair is significantly less than that of the single aircraft. At cruising lift coefficients, between 0.4 and 0.5, the efficiency factor of the coupled pair is approximately 75-percent of the efficiency factor of the single aircraft. Thus, the effective aspect ratio is not doubled; it is only increased by about 50-percent. In consequence, the lift-drag ratio does not increase by over 40-percent (eq (4)), but only by about 20 percent. This situation would not be improved signficantly (as suggested by equation (3)) by flying the coupled pair at greater lift coefficient since the curves of e'_p vs C_L become relatively flat at the higher lift coefficients.

Even attaining the values of e'_p shown in figure 11 might require modifying the wing tips. The tips must join with a satisfactory pressure seal across the adjoining tips chords or else a slot effectively exists in the combined configuration. Even for the case of ideal spanwise loading, reference 5 shows that a slot having a width of 0.2 percent span reduces the efficiency factor by almost 24 percent and a 2 percent slot reduces it by over 32 percent.

Span-load distribution.- The heart of the induced-efficiency problem is the spanwise load distribution. Figure 12 compares the load distributions for the single and coupled pair of aircraft at equal lift coefficients. The existing single aircraft chosen for this calculation is typical of current wide-body transports in that the wing is designed to have less-than-elliptic loading near the tips, thus favoring structural weight at the expense of some increase in induced drag. When the pair of aircraft are joined at the wing tips, the result is a deep "valley" near the center of the load distribution. This result is in conformity with the previous more general calculation, and a rough interpolation between figure 10(b) and figure 12 indicates that the calculated efficiency factors of figure 11 are in conformity with the results obtained with $N = 2$ in figure 7.

Aircraft trim when coupled.- Examination of figure 12 indicates that, when coupled, the load distribution across each of the pair of aircraft is not symmetric about the centerline of each aircraft. Thus the two coupled aircraft experience individual rolling moments which tend to bank them away from each other. Because of the thin short-chord tips, these moments can not be countered by the aircraft structure without major structural redesign. Instead, the actual tip coupling must be "pinned" rather than "rigid" to eliminate moment carry-over between the aircraft. The rolling moments must be countered by the individual lateral control systems of the two aircraft. If lateral control is by means of tip-mounted ailerons, roll balance will deepen the "valley" in the center of the span-load distribution with a consequent further degradation of aerodynamic efficiency. If lateral control is by spoilers, there will be some effect on the load distribution, and, in all probability, some increase in profile drag. In the balanced-roll configuration it appears unlikely that the tip coupled pair of aircraft would be any more efficient than if they flew in staggered formation flight.

As indicated in figure 12, coupling increases the loads on the adjacent wing tips. Because of the swept wing, these tips are behind the center of gravity of the aircraft. Thus, the increased tip loads result in a diving moment. In the present case, this diving moment is equivalent to shifting the aerodynamic center rearward by 3.5 percent of the mean aerodynamic chord. (When the complete aircraft is considered, coupling also reduces the downwash at the tail producing an additional diving moment.) This diving moment must be countered by an additional download on the tail increasing the aircraft trim drag and countering some of the remaining small improvement in lift-drag ratio.

CONCLUSIONS

This study of the efficiency of tip-coupled aircraft systems indicates that within the limitations of an assumed two-term drag polar:

1. The lift-drag ratio of the coupled system can be expressed as a simple multiple of the maximum lift-drag ratio of the isolated units which comprise the system.

2. The number of units which can be combined into a coupled system operating at maximum lift-drag ratio is limited by maximum lift-coeffient, high-altitude engine characteristics, and poor performance of additional units climbing to couple into the system.

3. When the coupled system is operated at constant speed and altitude, the gain due to tip-coupling is severely limited even when an infinite number of

units are combined. If the chosen altitude is that for optimum performance of the isolated units, the system lift-drag ratio can be no greater than twice that of the isolated units.

4. The coupled system performance is further degraded by required compromises in span-load distribution. Distributions which yield good performance for the individual unit result in lessed efficiency for the coupled system.

5. The span-load distribution across a coupled pair of modern transports adversely affects the efficiency; the effective aspect ratio is only about 50 percent, rather than 100 percent, greater than a single aircraft. The control deflections required to maintain roll and pitch equilibrium further degrade the possible gain.

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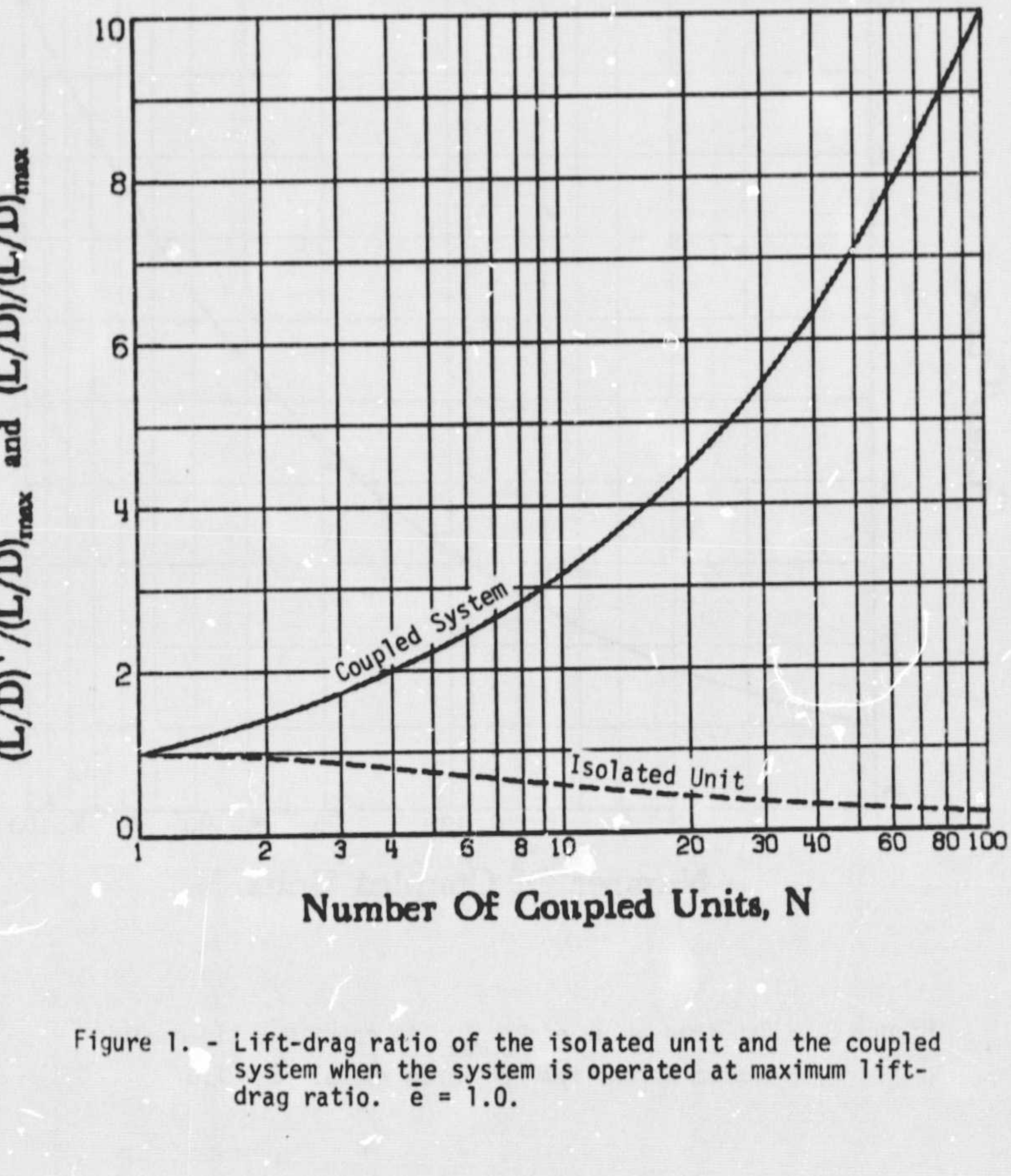


Figure 1. - Lift-drag ratio of the isolated unit and the coupled system when the system is operated at maximum lift-drag ratio. $\bar{e} = 1.0$.

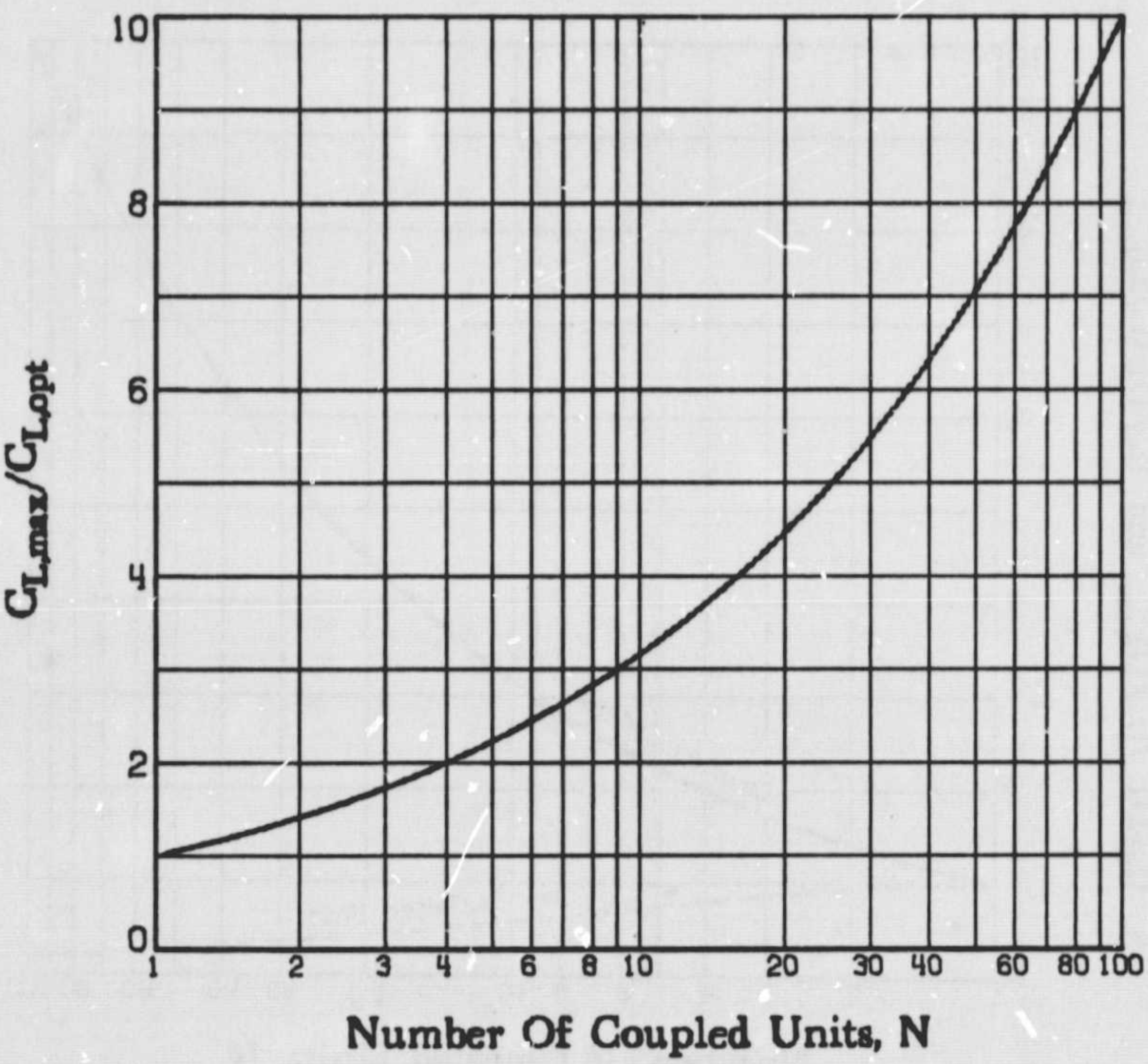


Figure 2. - Required value of $C_{L,max}$ to operate a tip-coupled system at maximum lift-drag ratio. $\bar{e}$ = 1.0

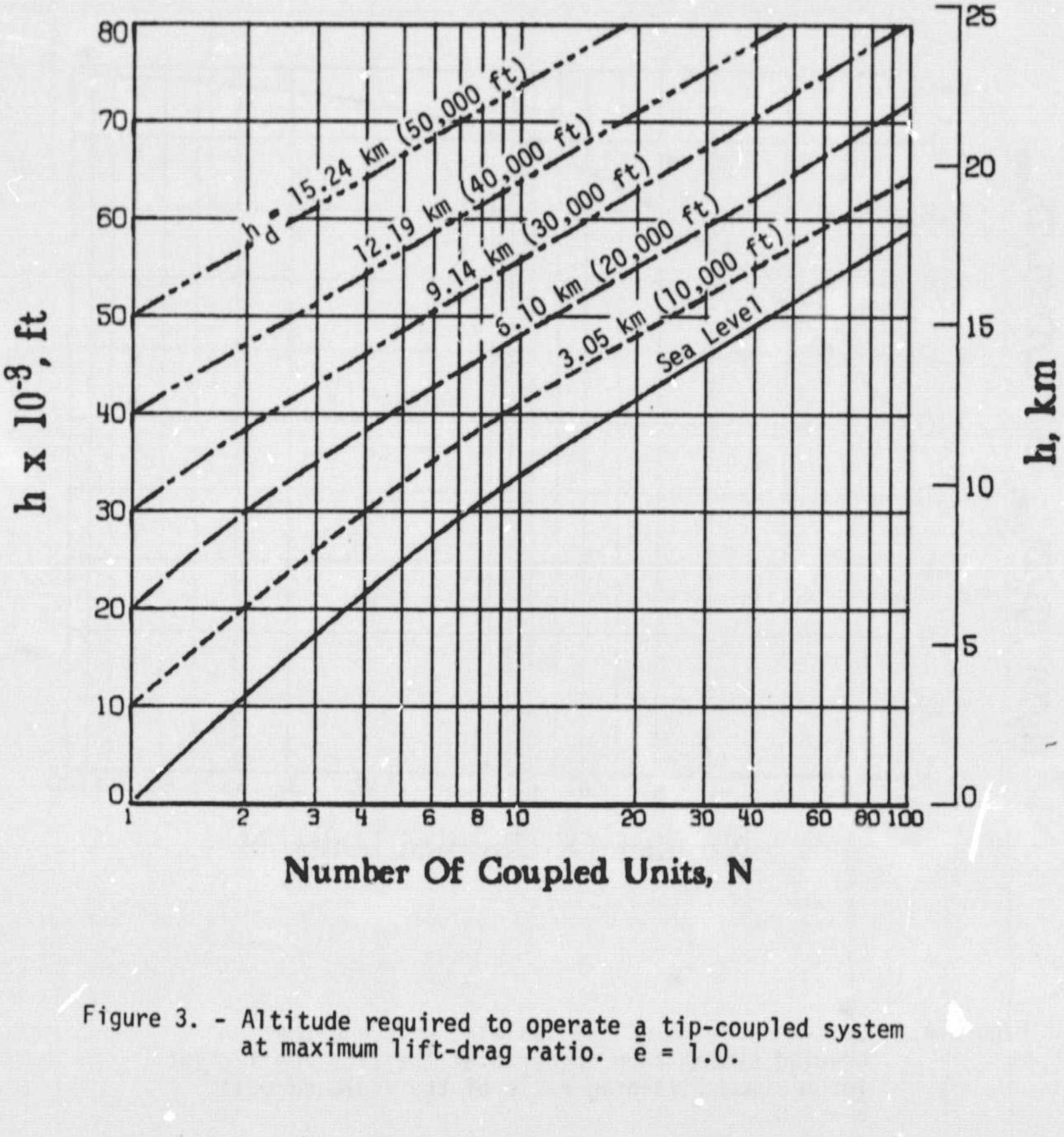


Figure 3. - Altitude required to operate a tip-coupled system at maximum lift-drag ratio. $\bar{e}$ = 1.0.

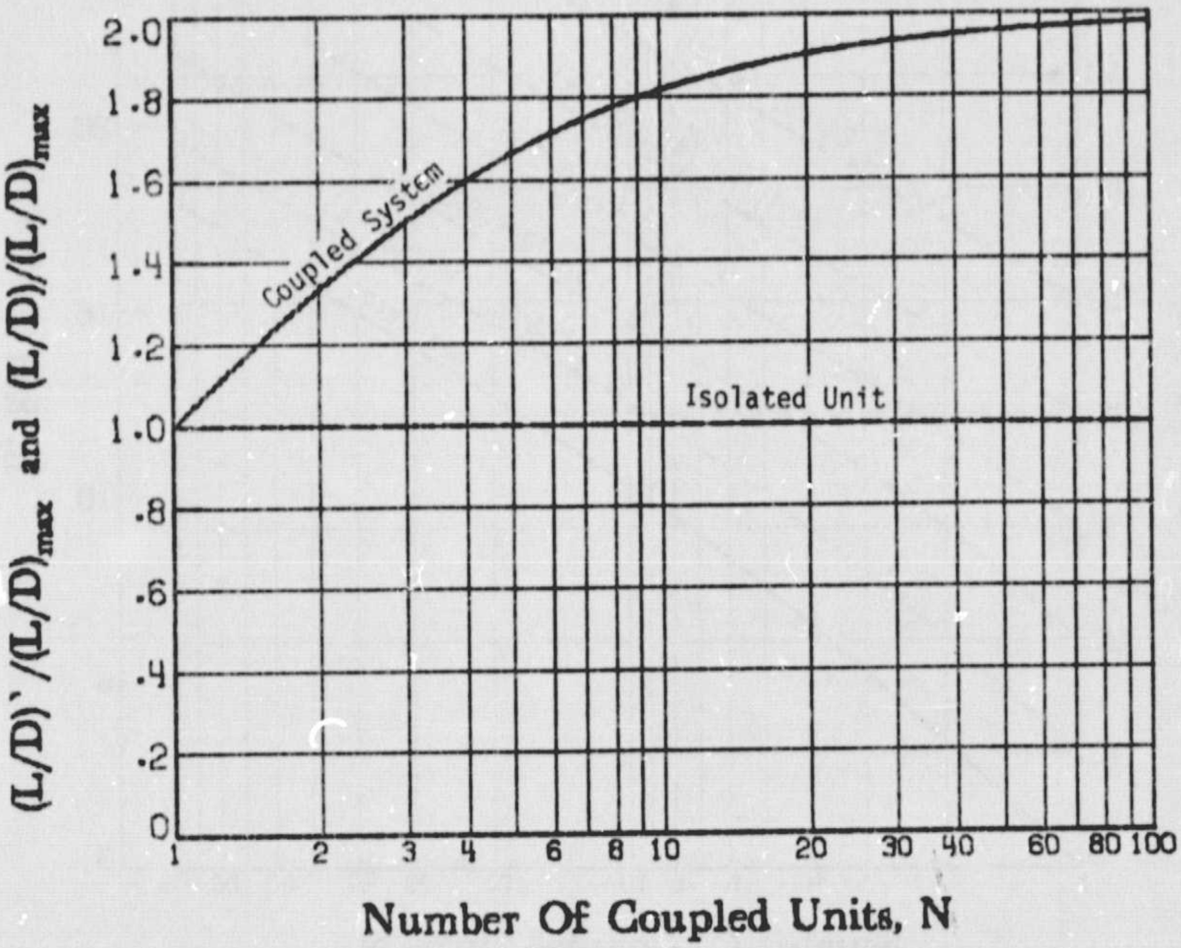
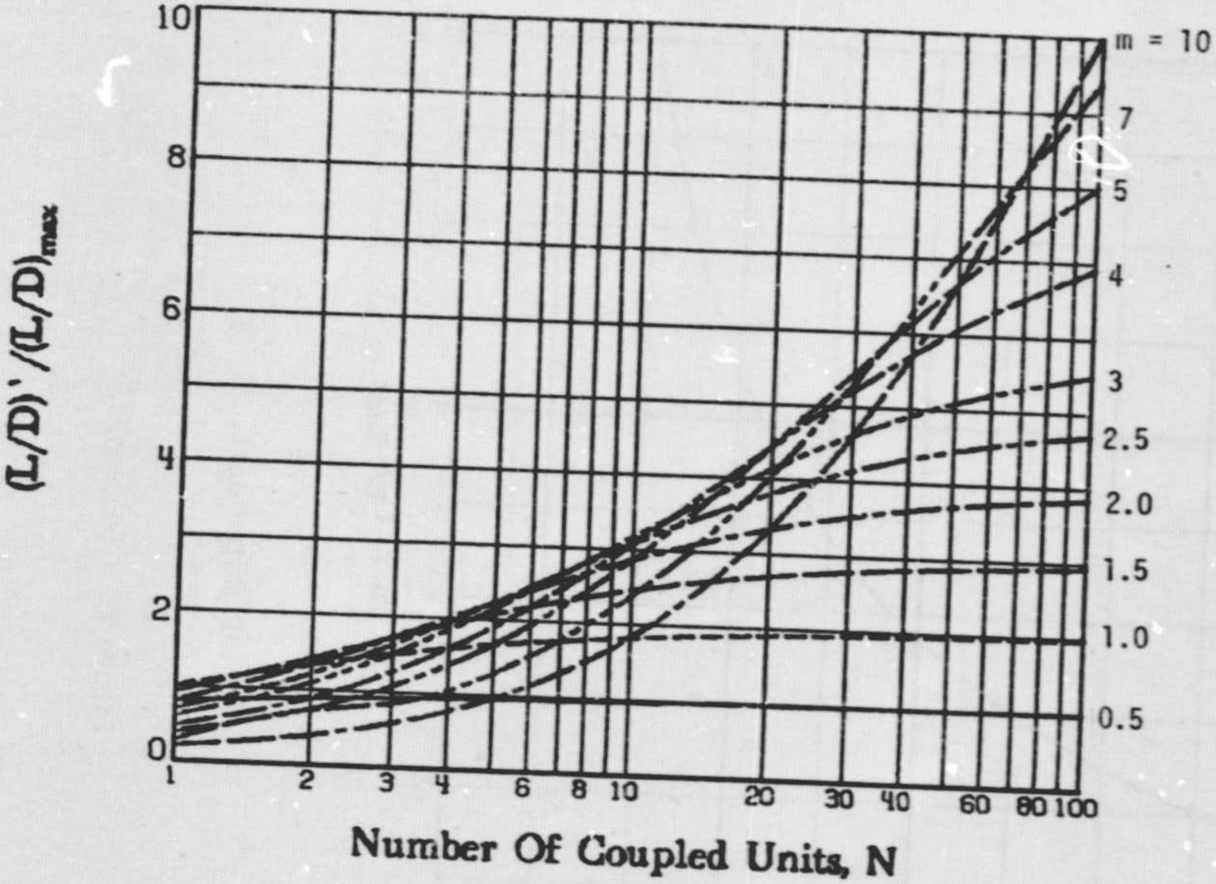
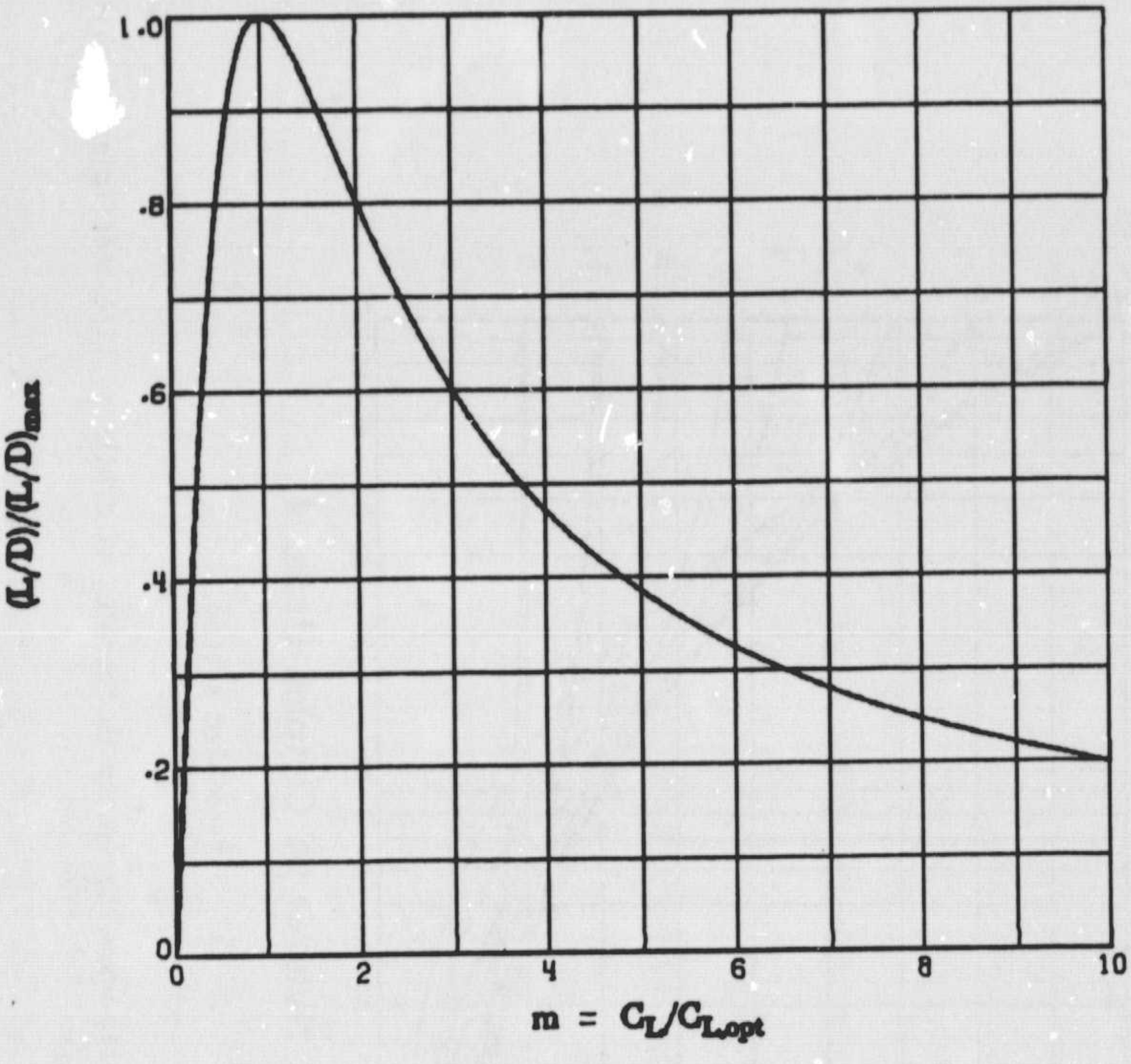


Figure 4. - Lift-drag ratio of the isolated unit and the coupled system when operated at the lift coefficient for maximum lift-drag ratio of the isolated unit. $\bar{e}$ = 1.0.



(a) Tip-coupled system.

Figure 5. - Lift-drag ratio when the system is operated at arbitrary lift coefficient such that $C_L = mC_{L,\ opt}$. $\bar{e} = 1.0$.



(b) Isolated unit.

Figure 5. - Concluded.

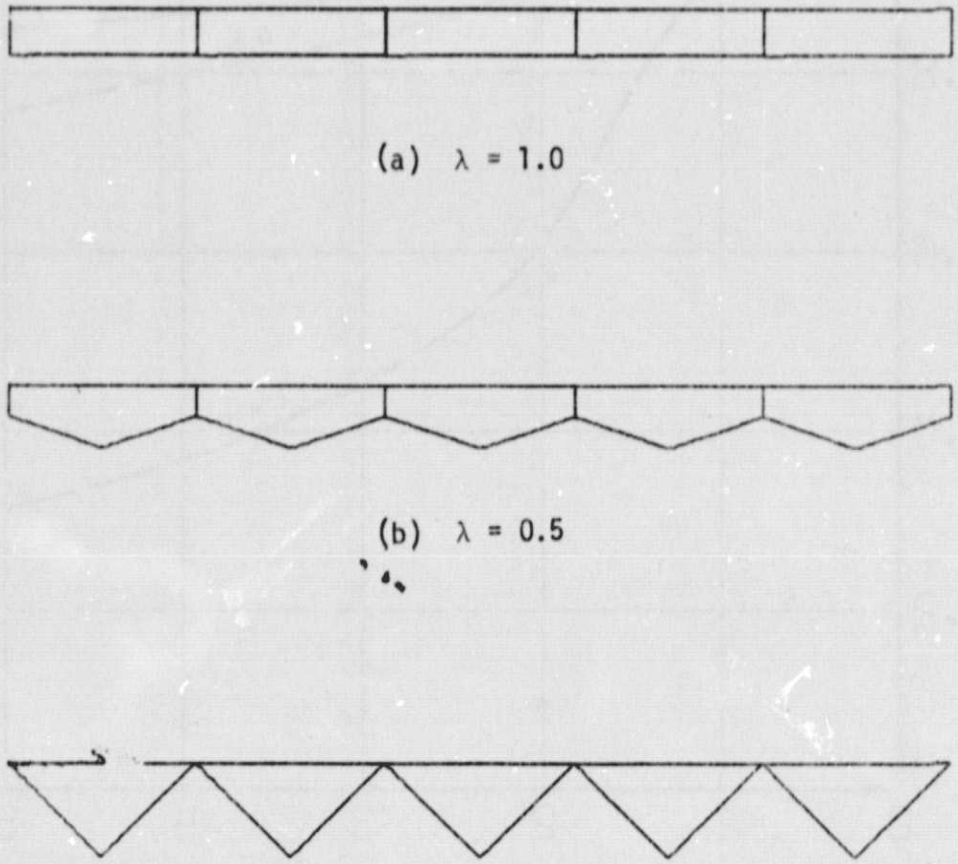


Figure 6. - Planforms of the tip-coupled systems. These planforms are shown for systems of five units each of which has an aspect ratio of 4.0.

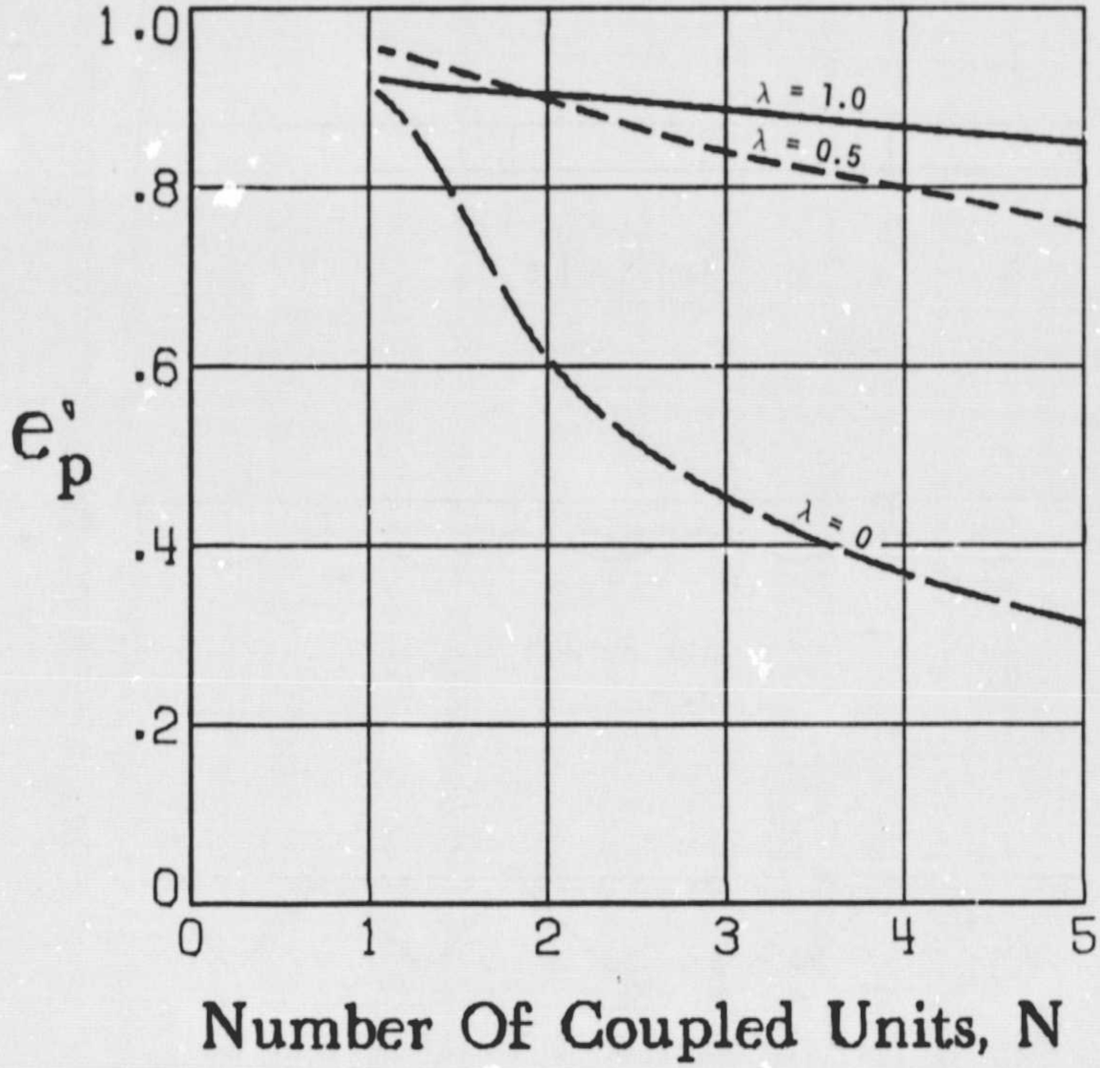


Figure 7. - Potential-flow efficiency factors for tip-coupled systems comprised of units with an aspect ratio of 4.0 and different taper ratios.

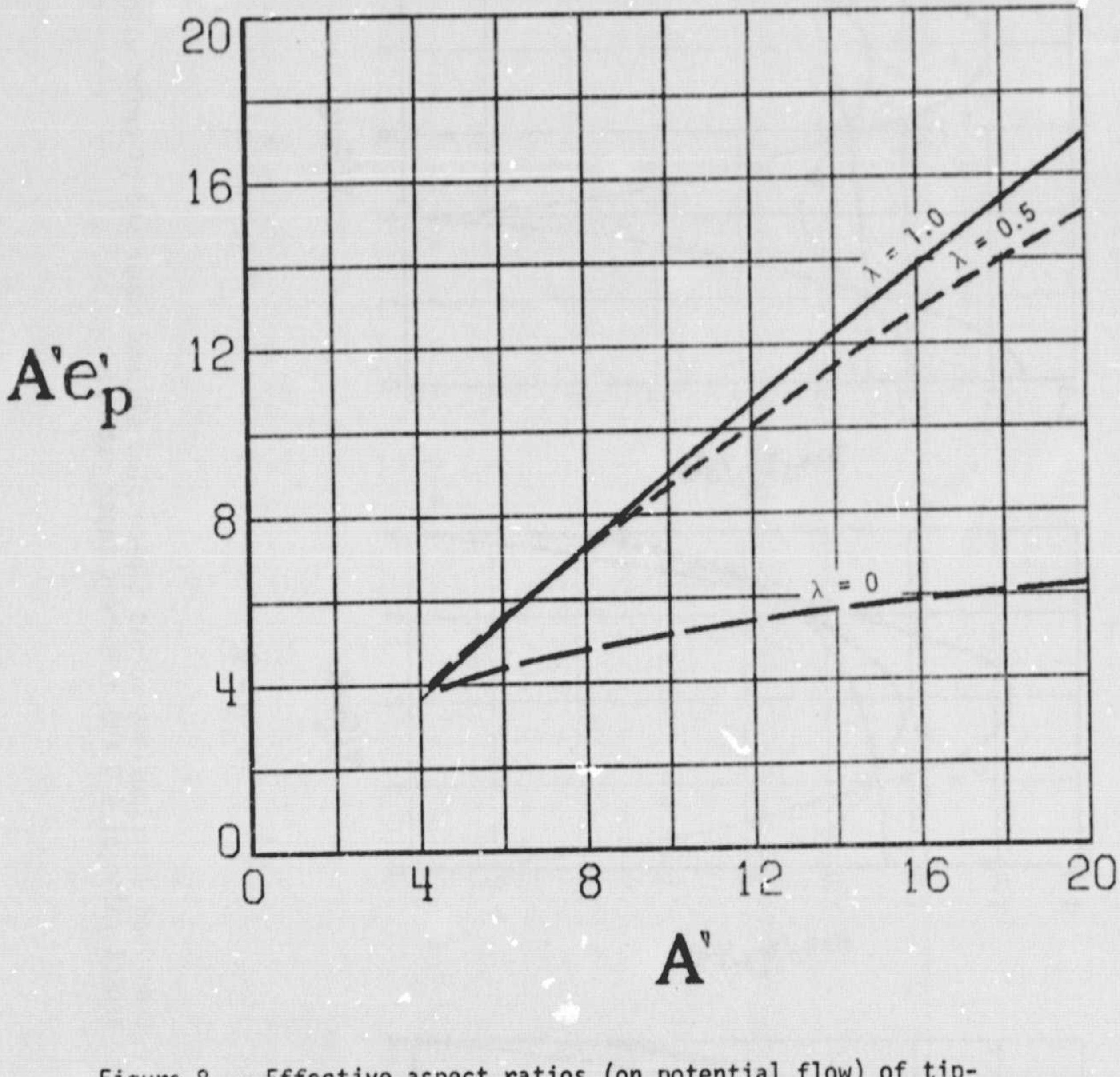
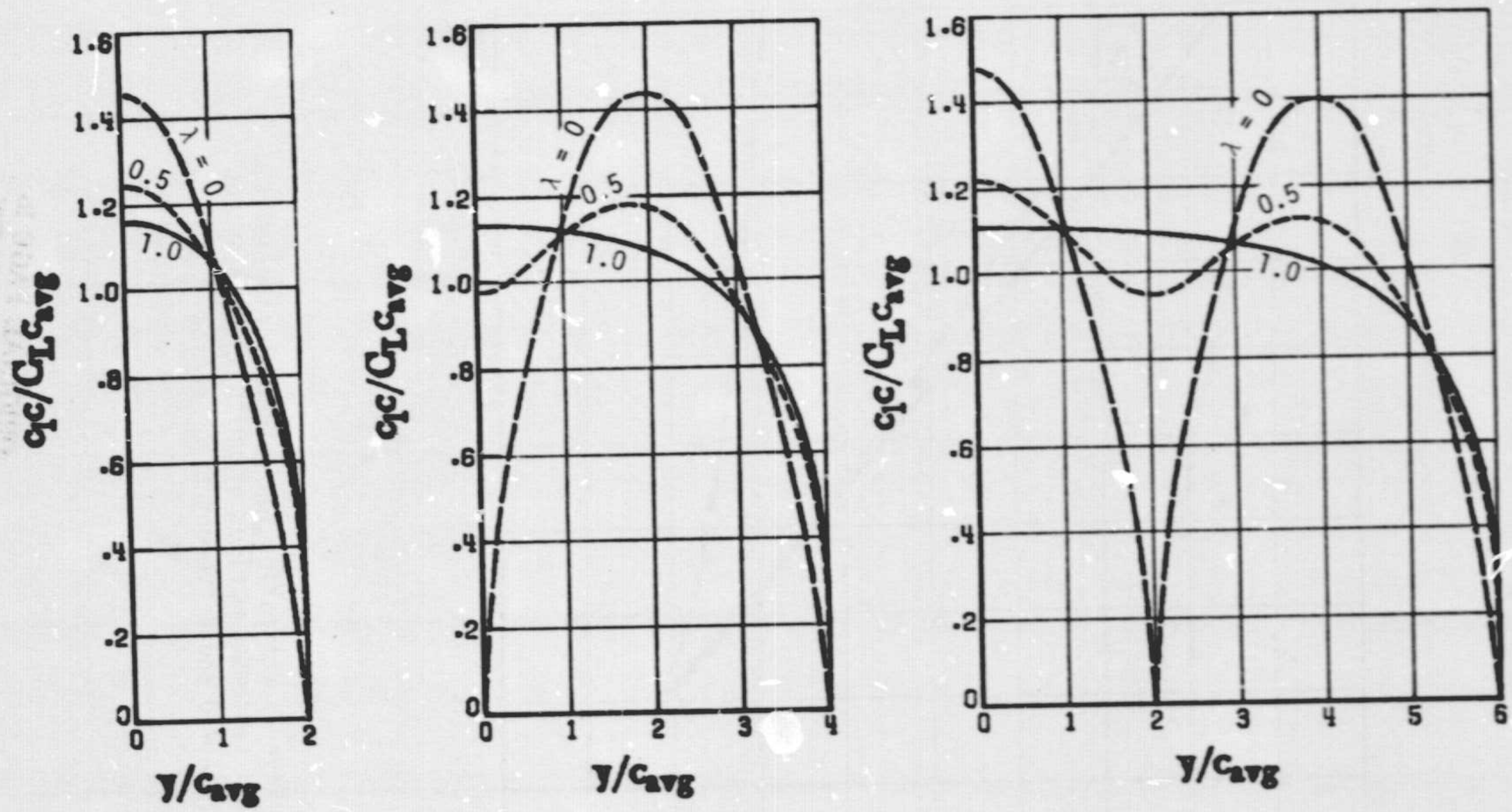
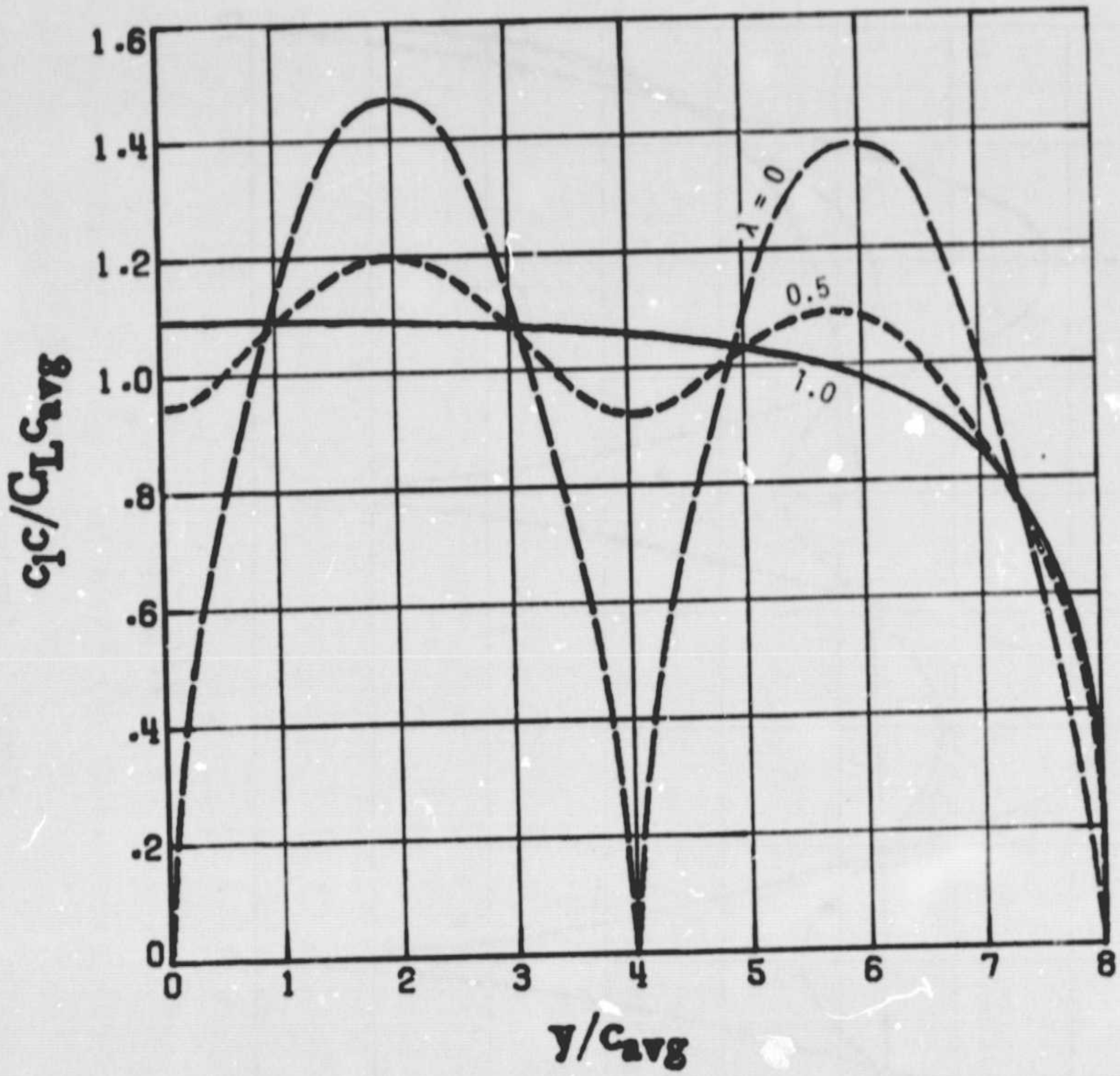


Figure 8. - Effective aspect ratios (on potential flow) of tip-coupled systems comprised of units with an aspect ratio of 4.0 and different taper ratios.



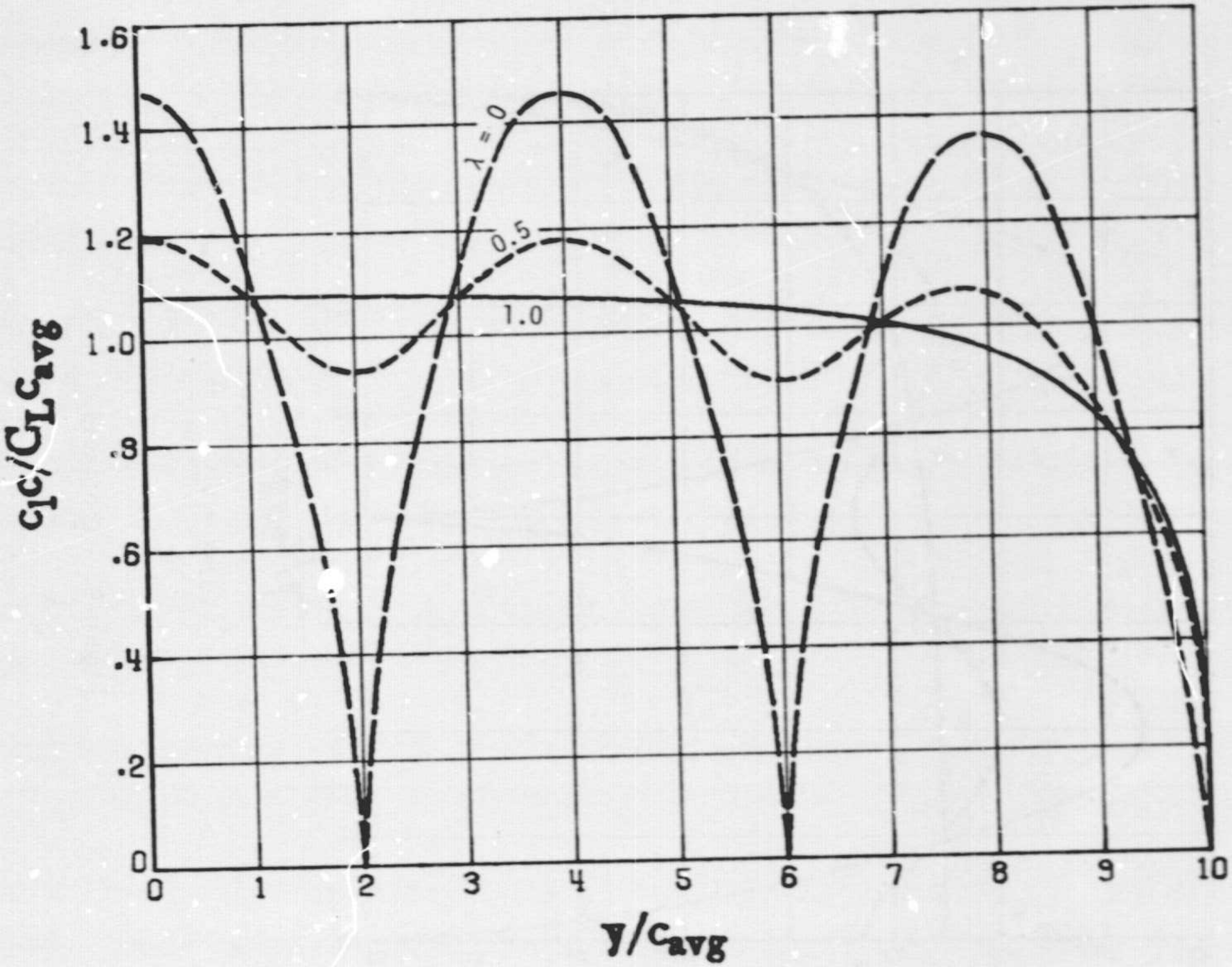
(a) N = 1 (b) N = 2 (c) N = 3

Figure 9. - Span-load distributions across tip-coupled systems comprised of units with an aspect ratio of 4.0 and different taper ratios.



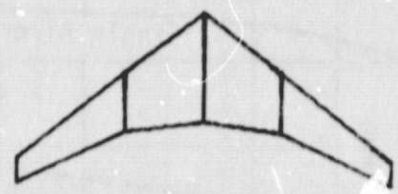
(d) N = 4

Figure 9. - Continued.

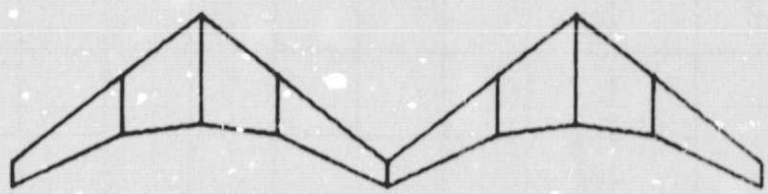


(e) N = 5.

Figure 9. Concluded.



(a) Single aircraft.



(b) Coupled pair.

Figure 10. - Planform of a modern wide-body transport aircraft when flying as a single aircraft and as a coupled pair.

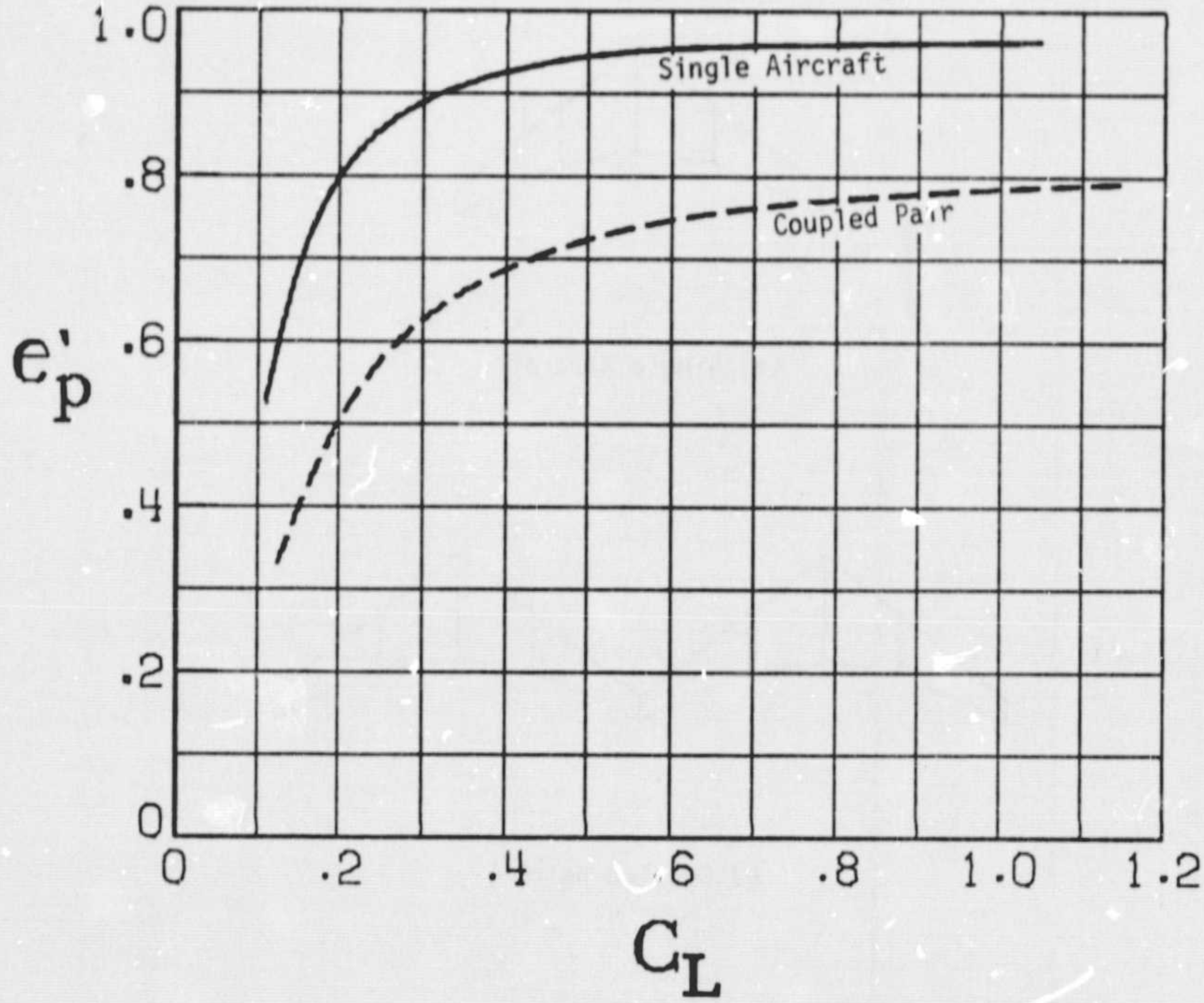
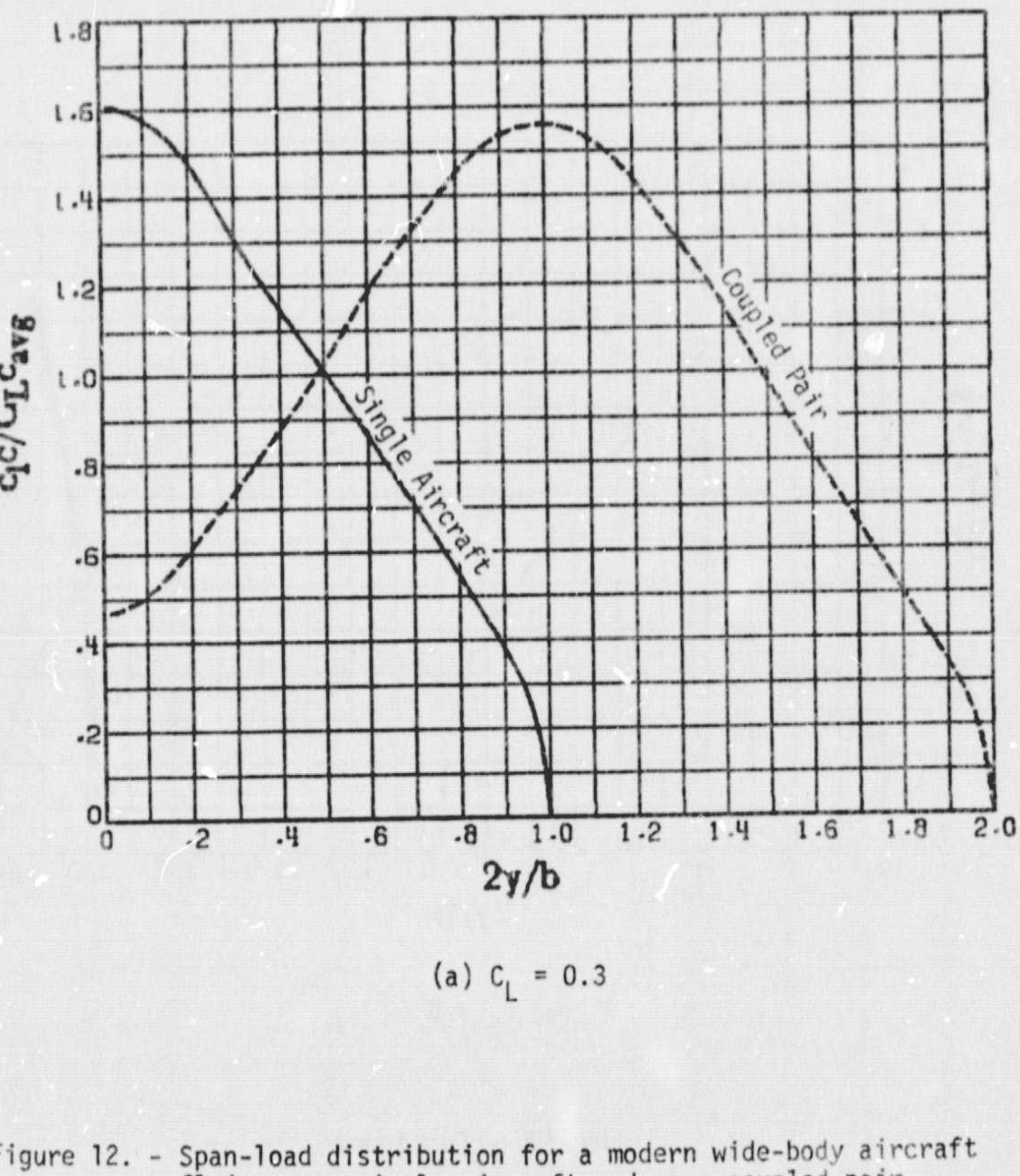


Figure 11. - Potential-flow efficiency factors of a modern wide-body aircraft flying as a single aircraft and as a coupled pair.



(a) $C_L = 0.3$

Figure 12. - Span-load distribution for a modern wide-body aircraft flying as a single aircraft and as a coupled pair.

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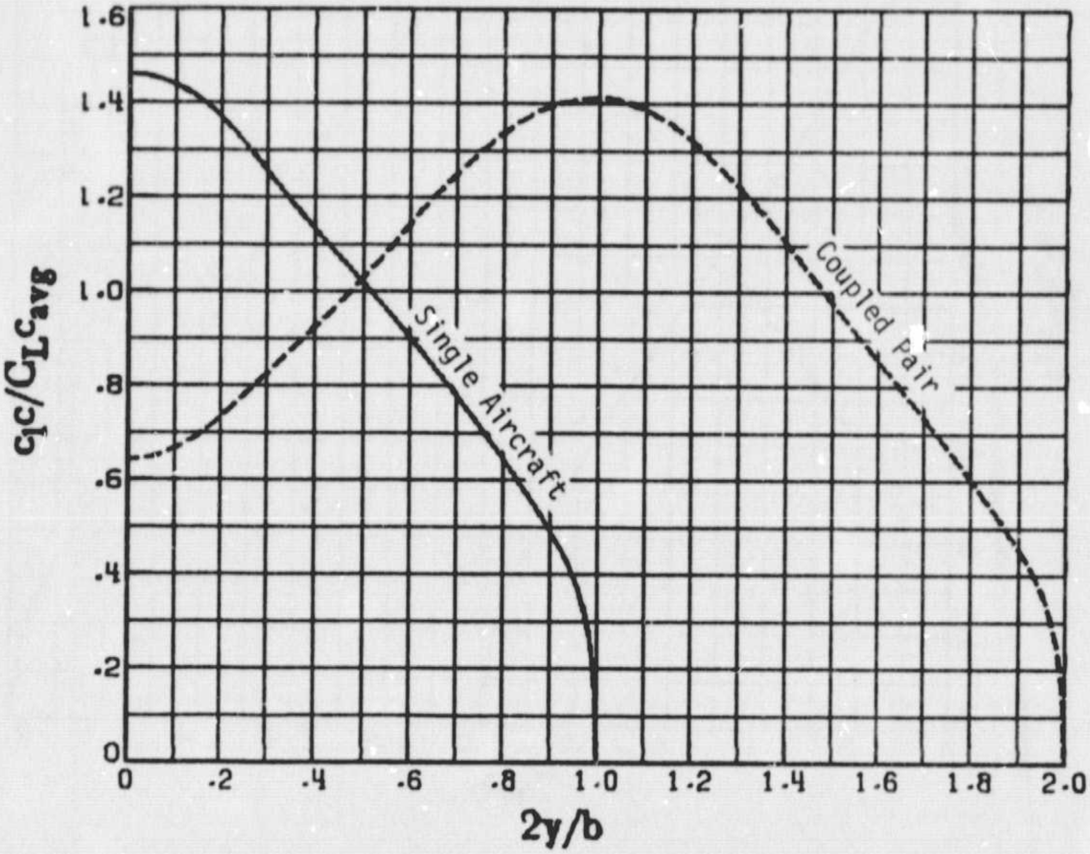
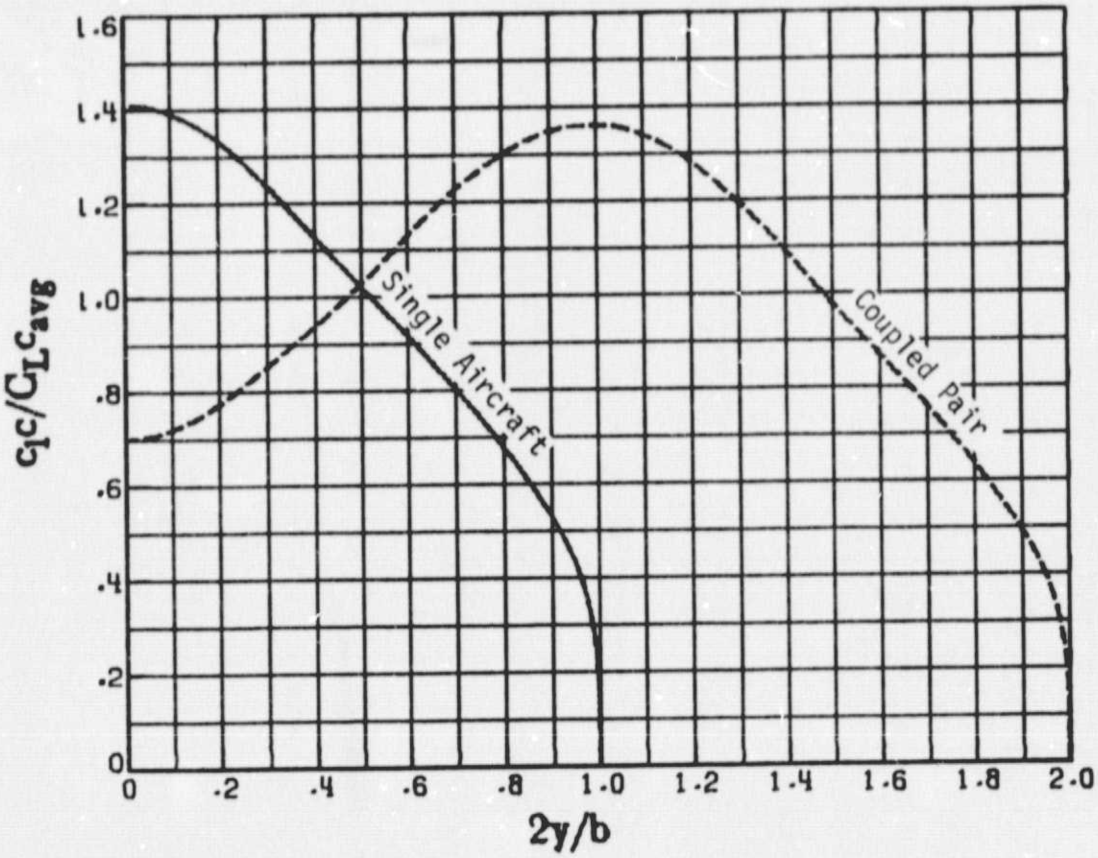


(b) C_L = 0.6

Figure 12. - Continued.



(c) $C_L = 0.9$

Figure 12. - Concluded.

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15. Supplementary Notes

16. Abstract

It is shown that the lift-drag ratio of tip-coupled systems can be expressed as a simple multiple of the lift-drag ratio of the isolated units comprising the system. When operated for maximum lift-drag ratio, the extent of the coupled system is limited by maximum lift coefficient, high-altitude engine characteristics, and degraded performance of the isolated unit climbing to couple into the system. When operated at constant altitude, the gain from coupling is severely limited. If the cruise altitude is that for best performance of the isolated unit, the system lift-drag ratio can be no better than twice that of the isolated unit even when an infinite number of units are coupled. System performance may be further degraded since span-load distributions which yield good performance for the individual units reduce the efficiency of the coupled system.

Coupling a pair of modern transport aircraft results in only about half the expected gain because of a poor span-distribution across the coupled pair. The control deflections required to maintain roll and pitch equilibrium further degrade the possible gain.

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