A New Concept of PAR WIG for Commuter Transport

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PART A Horizon for designing WIG

1 BASIS FOR HORIZON

This is partially cited from Ref. 2, which accounts following facts:

① Transportation Efficiency Parameter(=TEP);

◇ To compare operational efficiency of WIG with that of airplane, a new TEP is introduced[3)]

$$TEP = M(WV_{cr}/P_{cr}) \qquad \text{See Fig. 1.} \qquad (0)$$

where P_{cr} is power required for cruising, V_{cr} is cruising speed and $M \equiv V_{cr}/a_{SL,ST}$. It replaces "specific power" of Ref. 8.

◇ Higher speed of 400～500km/h is desired for obtaining higher TEP, especially on big WIG. See Fig. 1.

◇ TEP of WIG should be evaluated as mean-in-year covering both IGE and quasi-OGE flights. Statistical data[6)] of wave height is used. See Fig. 2.

② Satisfactory longitudinal flying quality (for conventional airplane type);

This may be obtained from rather low lift coefficient at IGE cruise, say about 0.6[3)]:

→ reduced wing camber or S-type camber[1)],

which brings close three longitudinal points at IGE cruise,

CG, center-of-lift, and 1/4 chord position of the main wing. Also no trim loss at IGE cruise.

③ C_{DP}

Low parasite drag coefficient C_{DP} brings triple merits;

→ high speed →high TEP,

→ high L/D →high TEP,

→ low C_L at IGE cruise →②.

Hence C_{DP} must be reduced to the level of excellent land-based airplanes[3];

retractable steps and wheels as well as drastically reduced end-plates -- suggested by Russian recent concepts-- must be used.

④ High-lift device

This is required by the following two reasons.

i) To obtain satisfactory PAR take-off performance with a "composite wing" of A=6: See section 4.3(2)b).

Sufficient elongation of wing chord, about 1.6 times, is needed[4].

ii) To obtain high wing loading for excellent IGE cruise performance, because of high speed at cruising:

High C_{LLO} is needed with permissible take-off speed V_{TO}, at the end of take-off when PAR effect is closed. See Eq.(9a).

2 NOMENCLATURE

A	; geometrical aspect ratio of main wing	
A_{eff}	; effective aspect ratio of main wing	
$a_{SL.ST}$	; sonic speed at sea level standard day	m/s
b	; span of main wing	m
B/L	; span of main wing / overall length of vehicle	
C	; chord length of main wing	m
C_L, C_{LOPT}	; lift coefficient, and the optimum value	

C_D, C_{DP}; drag coefficient, parasite drag coefficient

HW = wave height, from bottom to peak m

HWDT ; design wave height m

HWI ; min (HWDT, QHW) m

QHW ; wave height at "quasi-OGE" flight, 3.5m is used later.

h_{min} ; Aerodynamically effective flight height;
height of wing lowest point from mean water surface m

L ; lift (kgf), or overall length of vehicle (m)

M ; $V/a_{SL,ST}$, quasi-flight Mach number

P ; power required at cruise watt, horse power, or kgf・m/s

PAS ; number of passenger (including crew) in a vehicle

PHW(x); function of probability for wave height to exceed x meters[6]

ρ ; air density at sea level standard day $kgf.s^2/m^4$

S ; area of main wing m^2

SEA =1 in harbor for PAS< 10, =2 in North Pacific Ocean for PAS> 10

T ; thrust kgf

TEP ; transportation efficiency parameter[2], See Eq.(0)

V ; flight speed (mainly cruise) m/s

V_{TO}, ; take-off speed (without PAR-effect) m/s

V_{cruise}; flight speed at cruise m/s

W, W_F ; gross weight, fuel weight installed kgf

WlP ; weight of one passenger and his baggage kgf

η ; propulsive efficiency , TV/P at cruise

◆ Abbreviations ;

◇ IGE, OGE; In-Ground-Effect, Off-Ground Effect, respectively

◇ PAR-WIG; Power-Augmented-Ram Wing-in-Ground

3 METHOD OF COMPUTATION

3.1 Basic Assumptions

3.1.1 For size and/or weight

(a) Overall length of WIG vehicles must be sufficient to accomodate the whole passengers. Therefore the rule of L vs. PAS for the conventional airplanes is statistically investigated, which gives

$$L=26.6(PAS/50)^{0.371} \quad (1)$$

(b) Aspect ratio of main wing

In this paper assumed directly is the ratio of span to vehicle length as 0.6, 0.8, and 1.0. Thus the aspect ratio is indirectly assumed. It seems that wing span may be primarily important because WIG motion in harbor may be influenced by it remarkably.

(c) W1P, weight of one passenger with his baggage, is assumed as

$$W1P=100\text{kgf}, \quad PAS \leqq 10$$
$$133\text{kgf}, \quad PAS > 10$$

This seems to be practically reasonable.

(d) Vehicle gross weight W is assumed as follows,

$$W(\text{kgf})=W1P \cdot PAS/0.35 \quad (2)$$

Thus the whole payload is 35% of the gross weight.

(e) Whole fuel weight installed W_f is assumed to be 15% of W.

3.1.2 Division of Wave height and flight mode

(f) Probability of wave height encountered

Shin-meiwa[6] presented a statistical data of wave height for Japan harbor and North Pacific Ocean. Based on it, the present author made Fig.2. The function PHW(x), the probabiliy for wave height to exceed x(m), is approximately formulated by the present author as below; $PHW(x)=\exp(-WK \cdot x^2)$ (3)

where WK=2.00 ("SEA=1"; in harbor), and

WK=0.35 ("SEA=2"; in North Pacific).

(g) Division of flight mode

◇ Design wave height HWDT is assumed as follows

$$HWDT = 10\% \text{ of wing span} \qquad (4)$$

Then we have $A_{eff} \sim 2A_G$. (See Eq.(10) and Fig.3)

◇ The whole wave hight is re-classified as follows;

When $HW \leqq HWDT$, HW is raised upto HWDT.

When $HWDT \leqq HW \leqq QHW$, HW is raised upto QHW($\equiv 3.5$m).

When $QHW \leqq HW$, HW is cut down to QHW.

According to reference 6 and also seen from Fig.2, the last case happens less than 5 % through a year; therefore this partial cut down may be insignificant.

◇ The whole flight mode is divided into the two kinds;

"IGE Flight" = Flight at HW=HWI=min(HWDT, QHW)

"Quasi-OGE Flight" = Flight at HW=QHW(=3.5m)

Thus we may think that it is practically unnecessary to do purely OGE flight (HW=∞), except for special purposes.

(h) h_{min}

h_{min}, in Eq.(10), designates the aerodynamically effective height of main wing, measured from the "mean surface" supposed from a rough water. In this paper the present author assumes as follows;

$$h_{min} = K_2 \cdot HW, \quad K_2 = 0.8 \qquad (5)$$

K_2 suitable for waves with triangular-peak shape would exceed 0.5 which is suitable to the sinusoidal wave shape.

3.1.3 Performance Parameters

(i) Parasite drag coefficient

$$C_{DP} = 0.017 + 0.013 \cdot EXP[-(PAS-1)/30] \qquad (6)$$

from which

$C_{DP} = 0.030,\ 0.028,\ 0.023,$ and 0.017

for PAS=1, 5, 25, and $\geqq 125$, respectively.

Maximum possible efforts must be paid, for example retractable steps and wheels as well as remarkably reduced wing end-plates etc.

(j) Propulsive efficiency

It is assumed as

$$\eta = 0.85 \cdot \{1. - 0.25 \cdot EXP[-(PAS-1)/20]\} \quad (7)$$

(k) Upper limit of take-off speed

We assume that it concerns with the final stage of lift-off, when PAR-effect is closed.

$$V_{TO}(km/h) = 80 \cdot PAS^{1/6} \cdot (1 - 0.05 \cdot PAS^{1/6}) \quad (8)$$

(l) Lift coefficient at the final take-off stage, C_{LLO}, is given by

$$C_{LLO} = 3.5 - (3.5 - 1.6) \cdot EXP(-(PAS-1)/30) \quad (9)$$

from which

C_{LLO}=1.60, 1.84, 2.65, 3.47, and 3.50

for PAS=1, 5, 25, 125, and 625 respectively.

3.50 may be the upper limit for mechanical flap. Wing loading is determined indirectly by using Eqs.(8) and (9) as follows

$$W/S = (1/2)\rho V_{TO}^2 \cdot C_{LLO} \quad (9a)$$

(m) Effective aspect ratio etc. at IGE cruise

Assuming the so-called parabolic formula at cruising condition, the following formulas are used[5];

$$A_{eff} = A_G[1 + 0.1\ SQRT(A_G \cdot S)/h_{min}] \quad (10)$$

$$C_{Lopt} = SQRT(\pi C_{DP} A_{eff}) \quad (11)$$

$$(L/D)_{max} = 0.5\ SQRT(\pi A_{eff}/C_{DP}) \quad (12)$$

Note that increase in C_{DP} brings triple damages (1-③);

decrease in lift/drag ratio → lower TEP directly,

increase in C_{Lopt} → lower cruise speed and TEP,

ditto → higher camber

poor longitudinal flying quality.

3.1.4 Engines

(n) In view of TEP, installed power and installed number of engines are rather unessential[3], and so are not considered in this paper.

[Note]

Less number of installed engines yields less maintenance cost (merit) and more installed power(demerit), which resuts from the condition of one-critical-engine failure. The recent trend seems to favour less number of installed engines.

3.1.5 Others

(p) Suggestions for horizontal tail volume

The lift coefficients in IGE cruise obtained later in this paper are 0.6～1.0. Then, as stated in section 1-②, WIG would have longitudinally satisfactory flying quality. So the horizontal tail volume seems close to that of conventional airplanes, say 0.5[7].

(q) Method to evaluate year-mean

The year-mean values of various quantities are obtained as follows

$$( )_A = [1-PHI(HVI)] \cdot ( )_{IGE} + PHI(HVI) \cdot ( )_{OGE} \qquad (13)$$

3.2 FORTRAN Program Structure

Fig.4 shows the FORTRAN program structure.

4 DISCUSSION

4.1 Ilustration of Assumptions

Fig.5 shows some input parameters such as SEA, NE, W/S, C_{LLO}, V_{TO}, C_{DP}, and η against PAS. Variations of them with PAS seem to be reasonable. Note that W/S is not an input, but rather an output.

4.2 Computed Result and Discussions

(1) Table 1 shows an example of output obtained using the FORTRAN program.

Table 1 also shows cruise range for fuel weight of 15% gross weight;

1785-3280 km (about 2610 km for A=6) for PAS=25

and 3200-6300 km (about 3770 km for A=6) for PAS=625.

The data for PAS=25 was used for the concept shown in Fig.7.

(2) Fig.6a shows computed outputs such as

AR,

wave height at IGE cruise,

PHW(HWI),

lift coefficient at IGE cruise,

and speed at cruise averaged in year.

Breaks of the PHW(HWI) between PAS=5 and 25 result from the assumed variation of SEA.

C_L at IGE cruise have values of 0.6～0.9, and so desirable.

Cruise speeds(year-mean), for large vehicles, are 400～500 km/h, as also expected.

The marks ○ correspond to points where the aspect ratio of main wing is approximately 6. The present author wants to put his main interest at this value, as a promising PAR-WIG vehicles.

(3) Fig.6b shows L/D at cruise of IGE and of year-mean.

The values for A=6 are approximately shown by the marks

○ for broken curve (average in year)

and ● for solid curve (IGE cruise), respectively.

It is noteworthy that, even of year-mean and of A=6,

L/D exceeds 24 for PAS≧125 and

L/D ～ 20 for PAS=25

These values would encourege investigators in the field of WIG. At the bottom of Fig.6b, year-mean of M·L/D are shown. It is again suggested that WIGs for PAS≧25 are superior to commuter airplanes, because

◇ L/D of WIG is better,

◇ cruising speeds are comparable,

◇ terminal of WIG may be more close to city center.

Concludingly, we can possibly say that whole WIGs for PAS≧25 are well competitive to airplanes.

4.3 Consideration of WIG Aspect Ratio

In the above discussion, the author concentrates his intetest to WIG of aspect ratio A=6. The reasons will be described below.

(1) Merit of larger aspect ratio

- Transportation efficiency at cruise is better (See Fig.6b).

(2) Merit of smaller aspect ratio

a) Cruise speed is higher. The bottom of Fig.6a shows that difference of V_{cruise} for PAS=625 between B/L=0.6 and 1.0 is about 100 km/h.

b) PAR-effect during take-off stage is more satisfactory. This subject was investigated by the present author in Ref.4. It is found that when a "composite main wing[1]--as shown in Fig.7" is adopted, A=6 would be marginally accepted. See Fig.8. A=6 however would require substantial efforts on designing main wing as follows;

a) $C/C_{NF} \geqq 1.6$; somewhat elaborate high-lift devices should be equipped at both leading and trailing edges.

b) $h/h_{min}=1.0$; uniform height of main wing is prefered. Namely both end-plates and anhedral angle--although effective for seaworthiness--are not desirable.

c) $t_1/h_{min} \leqq 0.5$; height of flap-trailing-edge must be severely low. Then wave crests might often strike flap-trailing edge. This problem would be solved by using some type of flexible flap structure.

As a compromise between cruise and take-off, the present author would recommend to select A=6.

PART B A New Concept of The Present Author

1 INTRODUCTION

Fig. 7 shows a new concept of WIG carrying about 25 passengers, which seems excellent by the present author. The particulars are suggested in Table 1, and the scheme for engine installation is "GI-- Scheme C" named in Ref. 4).

2 MOTIVE AND HORIZON TO THIS CONCEPT

a) Decreasing jet noise and water spray--considerable defects of Russian famous "Orlyonok"-- while increasing PAR effect.

→ Ejector scheme

Entrained secondary air relaxes noise and spray.

Flat jet exhaust makes PAR effect on main wing predominant.

b) To overcome the condition of "one critical engine stop", with minimum number of installed engines which makes maintenance cost mimimum.

→ "Power-interconnection by gas" of only two lift jet engines for PAR effect. This scheme of power-interconnection hardly requires penalties such as weight and maintenance cost.

c) To avoid overlong nose for installing PAR thrusters. This decreases the moment-of-inertia and so improves longitudinal flying quality.

→ Ente-style, where PAR thrusters are mounted on the front tail, is effective.

d) To make parasite drag coefficient minimum.

→ smallest wing-end-plate, and/or retractable undercarriages.

e) To make weight of installed engines minimum

→ "GI-Scheme C" described in Ref. 4)

1=all cruising engine (turboprop) supports IGE cruise only.

Therefore re-starting of PAR engine is needed,

to do OGE cruise and/or maneuver even if 1=all cruise engine operative,

or to do all operations if 1=all cruise engine stops.

The ratio of (total installed engine weight)/(vehicle gross weight) may be about 5～6% for this scheme[4].

It is noteworthy that increase in parasite drag hardly occurs even at cruising condition when PAR effect is stopped, because then ejector is closed and reformed to be elevator.

3 PROBLEMS CONCERNING THE CONCEPT

i) Duct loss

Somewhat long ducts are needed from jet engines to the ejector.

But it is expected that the duct loss will be recovered by ejector.

ii) Material with heat-resistance for ducts

Stainless steel may be satisfactory.

iii) Reduction of partial range due to re-starting PAR engine

This may result from OGE flight or failure of cruising engine.

It seems that ratio of

(reduction of partial range)/(total block distance)

would be rather small.

CONCLUSION

PART A

A horizon for designing PAR WIG capable of OGE flight is presented. A systematic computation with a FORTRAN program scheme is presented. Some input parameters are suitably selected for every vehicle-size.

a) A new TEP is introduced, which is nondimensional and yields a constant limiting value.

   Higher cruise speed would be desired for WIG of higher TEP.

b) C_L at cruise are reduced to about 0.6; the merits are triple.

   → increase in cruising speed and TEP.

   → proximity of three points CG, 1/4 chord point, and center-of-pressure at IGE cruise

   → thus satisfactory longitudinal flying quality

   Low C_{DP} promotes these merits considerably.

c) A formula of probability of wave hight is established. Using it the year-mean of WIG TEP is computed from IGE and Q-OGE flights.

   In order to realise as excellent WIG TEP as possible, quasi-OGE flight--at HW=3.5m-- is considered in stead of pure OGE flight.

d) Bigger WIGs have better TEP, but even WIG of 25 passengers would be marginally competitive with commuter airplanes.

e) For "composite main wing" of WIGs, A=6 seems to be a reasonable compromise, between cruise and take off.

PART B A new concept is proposed.

The motive is to improve some defects of the Russian famous "Orlyonok".

To reduce noise and water spray, while increasing PAR effect.

For this purpose ente-type is recommended. The front tail installs an ejector at the trailing edge to yield PAR effect for main wing.

The main wing of "composite type" has aspect ratio of 6.

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Table 1. An example of output-print of the present computation scheme.

```
INPUT
  K1     K2 BSFC TVOTV TLOL  ART   TVO   QHW   SS
 .80   .80 .250 1.00  .50   4.0   .50  3.50 340.

OUTPUT
    PAS  SEA   WTON    L     S   WOS    CLLO  VTOKPH    CDP   YYTA
     1.    1    .3   6.2   6.4   45.   1.60     76.   .030   .638

  BOL   AR    B  HWI  PHW  RKMA VCRKHA CLCI YKHII YKHIQ YKHIA MLODA
  .6   2.2  3.7  .4  .76   914.   136.  .54  11.3   8.0   8.8   1.0
  .8   3.9  5.0  .5  .61  1298.   116.  .73  15.1  10.9  12.6   1.2
 1.0   6.1  6.2  .6  .46  1715.   103.  .91  18.9  13.9  16.6   1.4

OUTPUT
    PAS  SEA   WTON    L     S   WOS    CLLO  VTOKPH    CDP   YYTA
     5.    1   1.4  11.3  16.9   85.   1.84     98.   .028   .676

  BOL   AR    B  HWI  PHW  RKMA VCRKHA CLCI YKHII YKHIQ YKHIA MLODA
  .6   2.7  6.8  .7  .40  1283.   175.  .59  13.1   9.7  11.7   1.7
  .8   4.9  9.1  .9  .19  1820.   150.  .79  17.4  13.3  16.6   2.0
 1.0   7.6 11.3 1.1  .08  2343.   133.  .99  21.8  17.2  21.4   2.3

OUTPUT
    PAS  SEA   WTON    L     S   WOS    CLLO  VTOKPH    CDP   YYTA
    25.    2   9.3  20.6  46.5   200.   2.65     125.   .023   .786

  BOL   AR    B  HWI  PHW  RKMA VCRKHA CLCI YKHII YKHIQ YKHIA MLODA
  .6   3.3 12.3 1.2  .60  1785.   267.  .58  15.9  12.7  14.0   3.1
  .8   5.8 16.5 1.6  .40  2530.   229.  .78  21.2  17.8  19.9   3.7
 1.0   9.1 20.6 2.1  .24  3280.   204.  .97  26.5  23.3  25.8   4.3

OUTPUT
    PAS  SEA   WTON    L     S   WOS    CLLO  VTOKPH    CDP   YYTA
    125.    2  46.4  37.4 110.0   422.   3.47     159.   .017   .850

  BOL   AR    B  HWI  PHW  RKMA VCRKHA CLCI YKHII YKHIQ YKHIA MLODA
  .6   4.6 22.4 2.2  .18  2925.   379.  .60  21.7  19.4  21.3   6.6
  .8   8.1 29.9 3.0  .05  3968.   330.  .80  28.9  27.7  28.8   7.8
 1.0  12.7 37.4 3.5  .02  5062.   294. 1.01  36.8  36.8  36.8   8.8

OUTPUT
    PAS  SEA   WTON    L     S   WOS    CLLO  VTOKPH    CDP   YYTA
    625.    2 232.1  67.9 345.0   673.   3.50     200.   .017   .850

  BOL   AR    B  HWI  PHW  RKMA VCRKHA CLCI YKHII YKHIQ YKHIA MLODA
  .6   4.8 40.7 3.5  .02  3216.   468.  .64  23.4  23.4  23.4   8.9
  .8   8.6 54.3 3.5  .02  4693.   387.  .93  34.1  34.1  34.1  10.8
 1.0  13.4 67.9 3.5  .02  6331.   333. 1.25  46.0  46.0  46.0  12.5

Stop - Program terminated.
```

SYMBOLS USED IN FORTRAN PROGRAM

ROU=ρ, K1=(C_L at IGE cruise)/(optimum C_L),
K2=(aerodynamically effective flight height)/HW,
TLOT=(tail-length)/(overall length of vehicle L),
ART=aspect ratio of horozontal tail,
TVO=typical value of horizontal tail volume for conventional airplane,
QHW= see the text, SS= sonic speed at sea-level standard day
WTON=gross weight (ton), WOS=wing loading,
YYTA=propulsive efficiency at cruise η

BOL=B/L, AR=aspect ratio of main wing, B=span of main wing (m)
HWI=see the text, PHW=PHW(HWI), RKMA=range(km) mean-in-year,
VCRKMA=cruise speed(km/h) mean-in-year, YKHII=lift/drag at IGE cruise,
YKHIA=lift/drag mean-in-year, MLODA=(M・lift/drag) mean-in-year

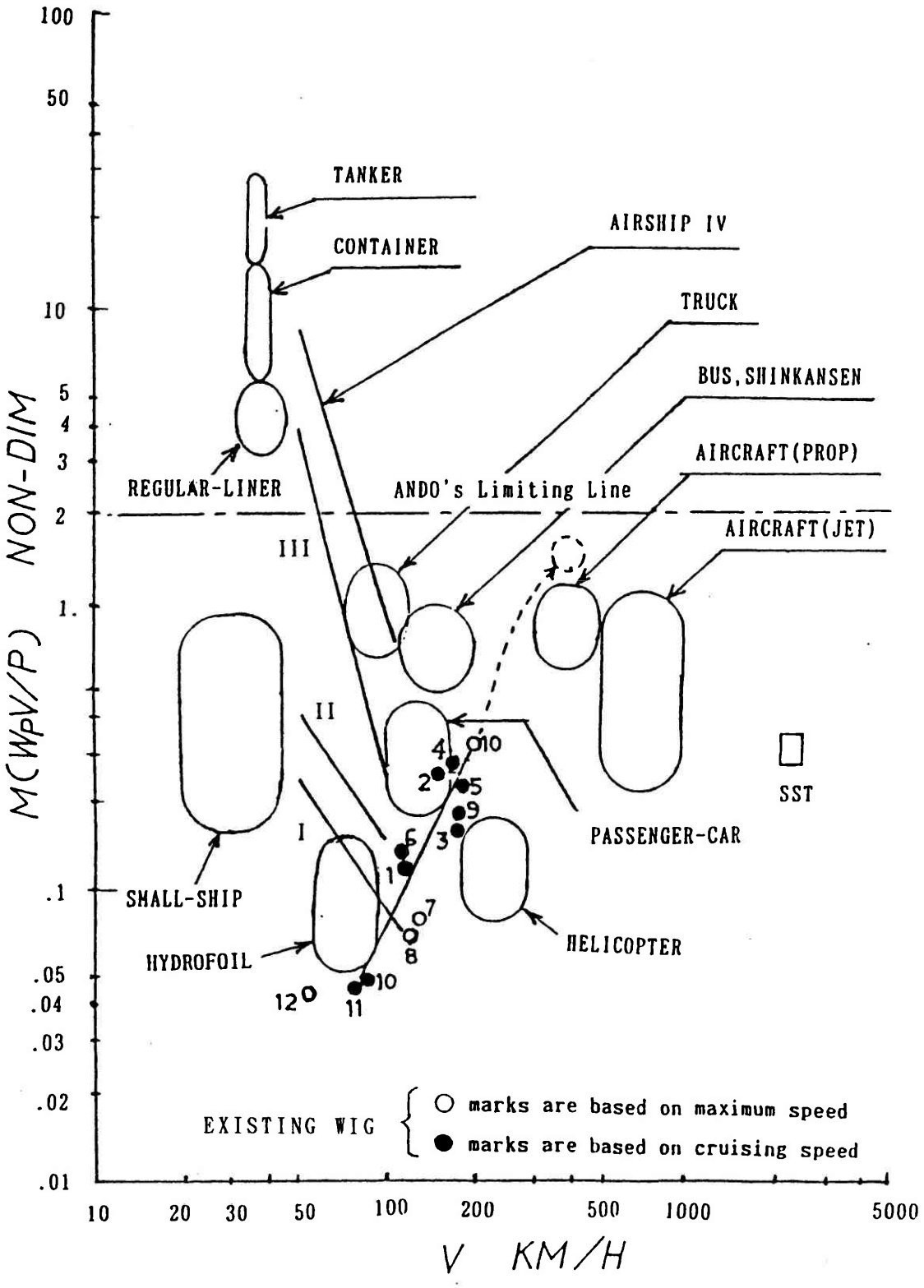


Fig. 1 ; New 'TEP': $M(W_PV/P)$ vs. V ; Only in this figure, exceptionally W_P= payload, P=installed power, V=maximum speed if not noted.

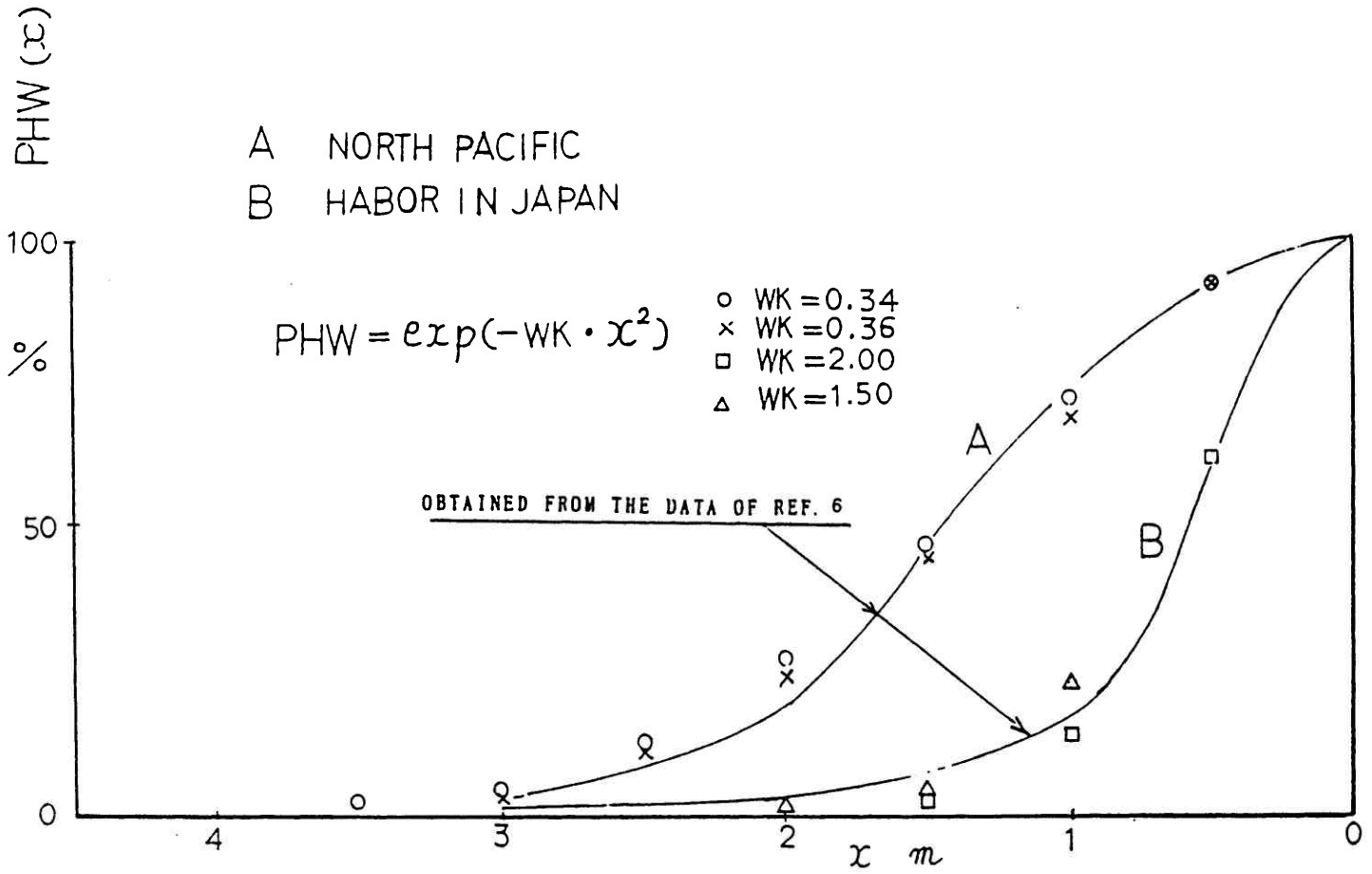


Fig. 2 Approximate formulation of probability of wave height, based on Ref. 6. PHW(x) means probability for wave heights to exceed x m.

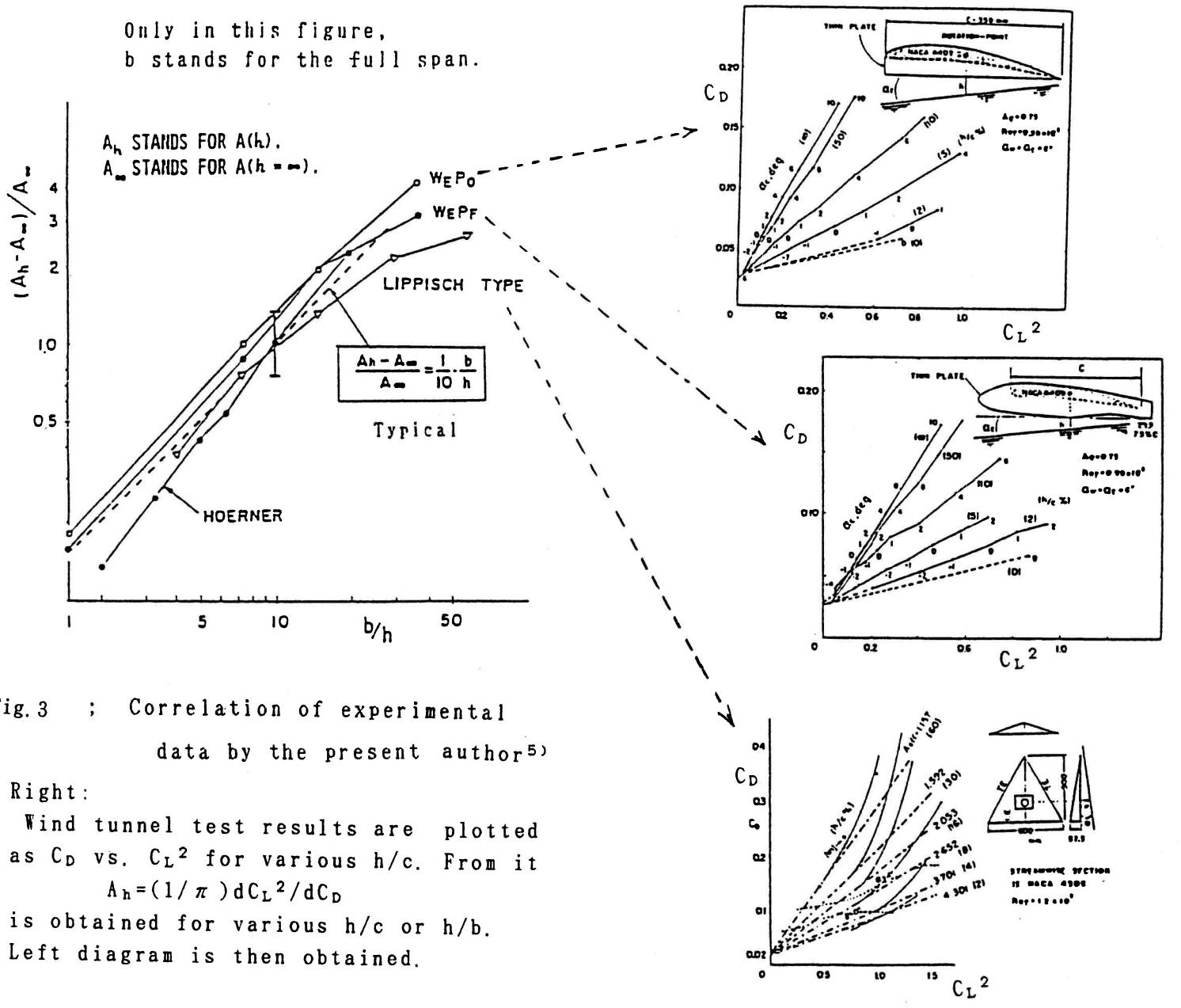


Fig. 3 ; Correlation of experimental data by the present author[5)]

Right:
Wind tunnel test results are plotted as C_D vs. C_L^2 for various h/c. From it

$$A_h = (1/\pi)\, dC_L^2/dC_D$$

is obtained for various h/c or h/b.
Left diagram is then obtained.

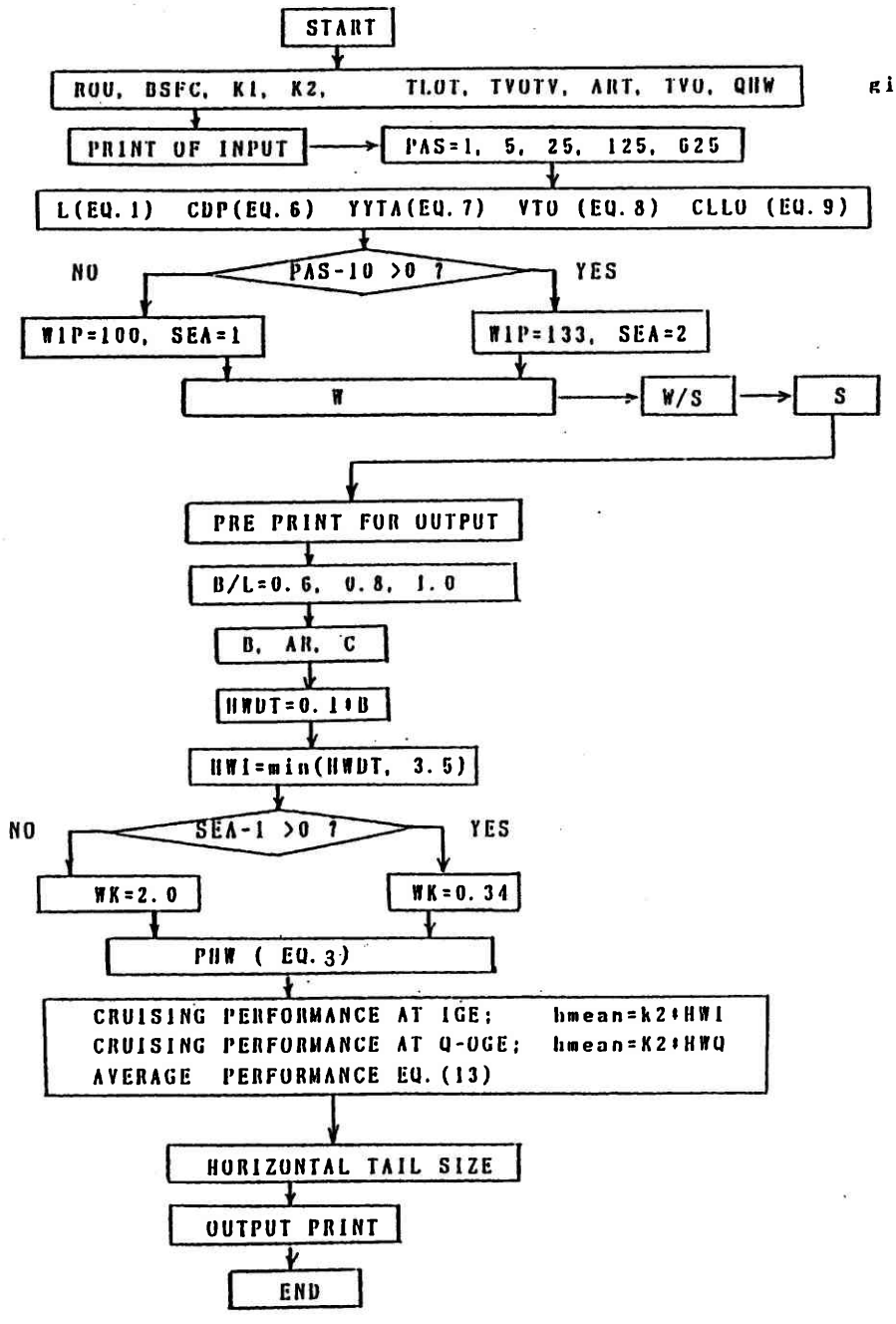


Fig. 4 Structure of FORTRAN program of the present computation scheme.

SYMBOLS USED IN FORTRAN PROGRAM

ROU=ρ, K1=C_{LCR1}/C_{LOPT}, K2=(aerodynamically effective flight height)/HW,
TLOT=(tail-length)/(overall length of vehicle),
ART=aspect ratio of horozontal tail,

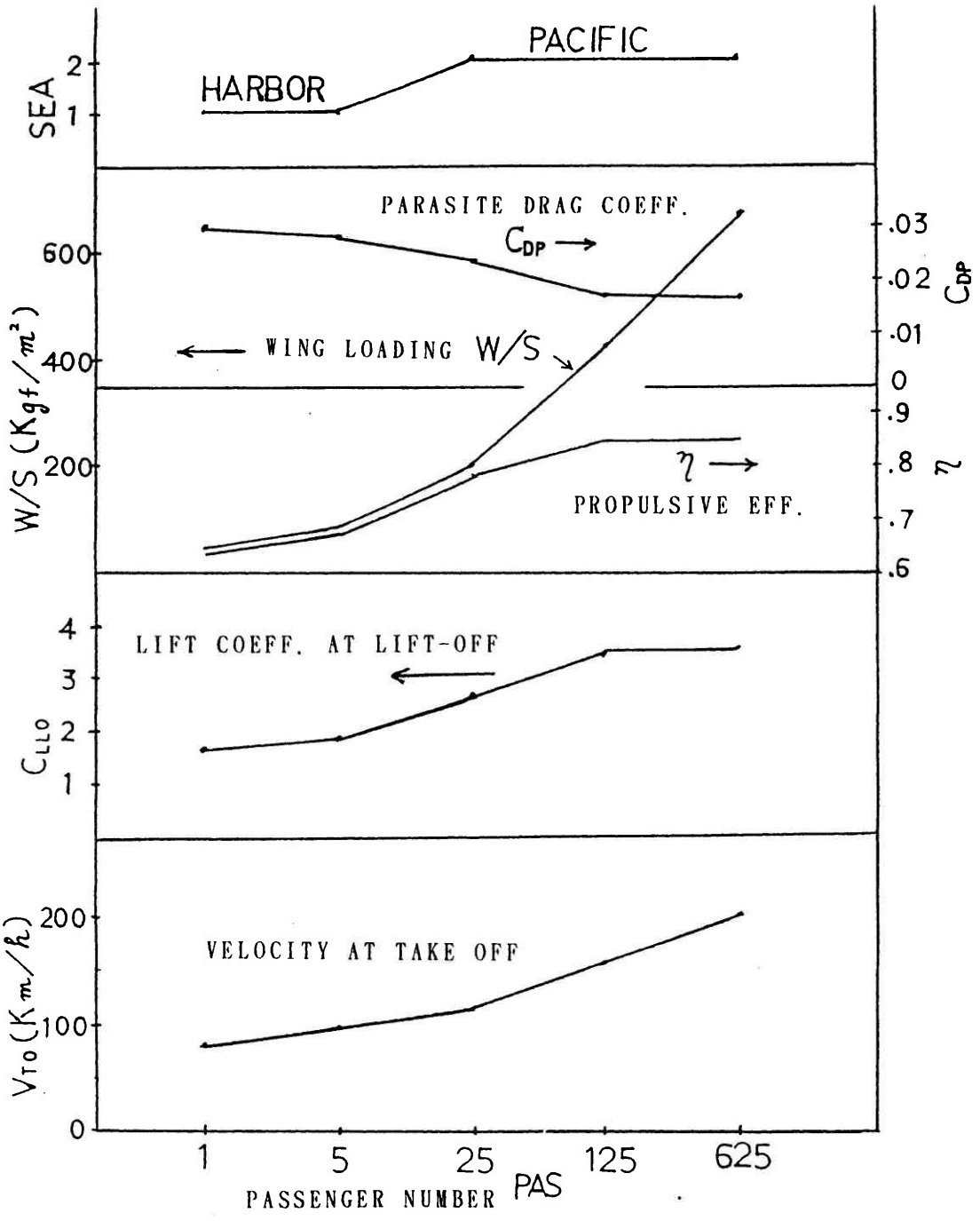
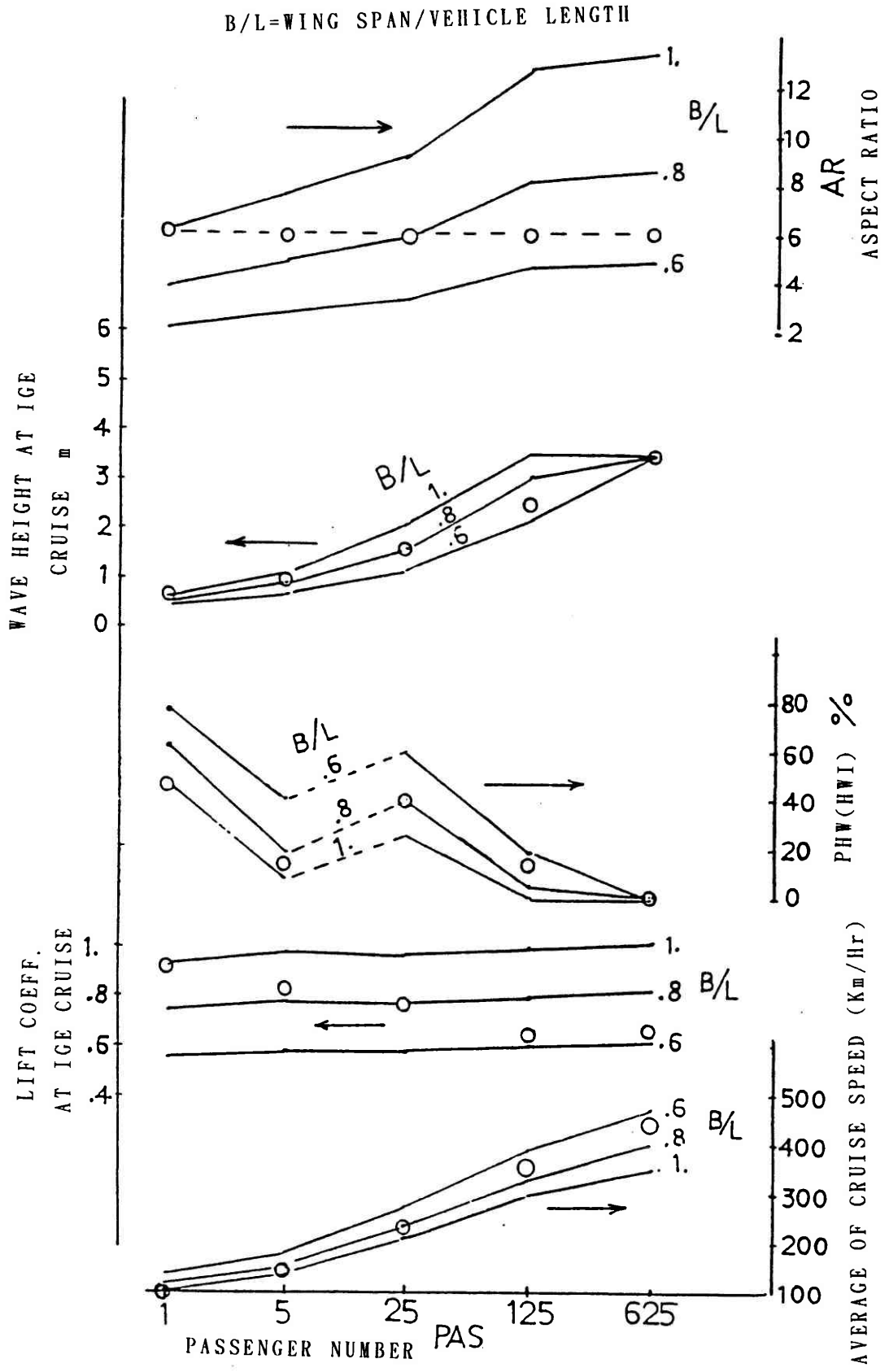
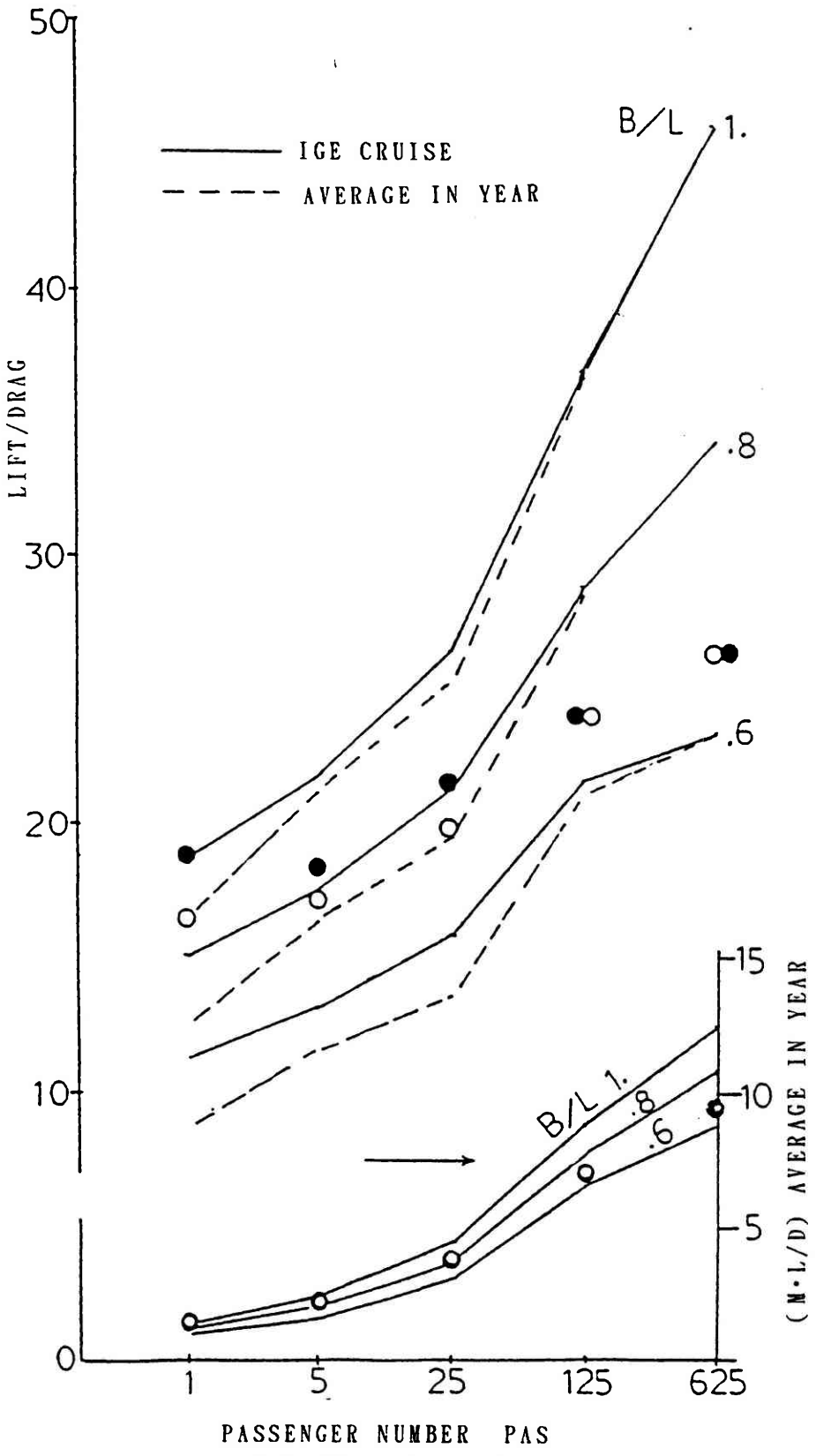


Fig. 5 Values of various parameters assumed, except for W/S, in the present computation vs. PAS.

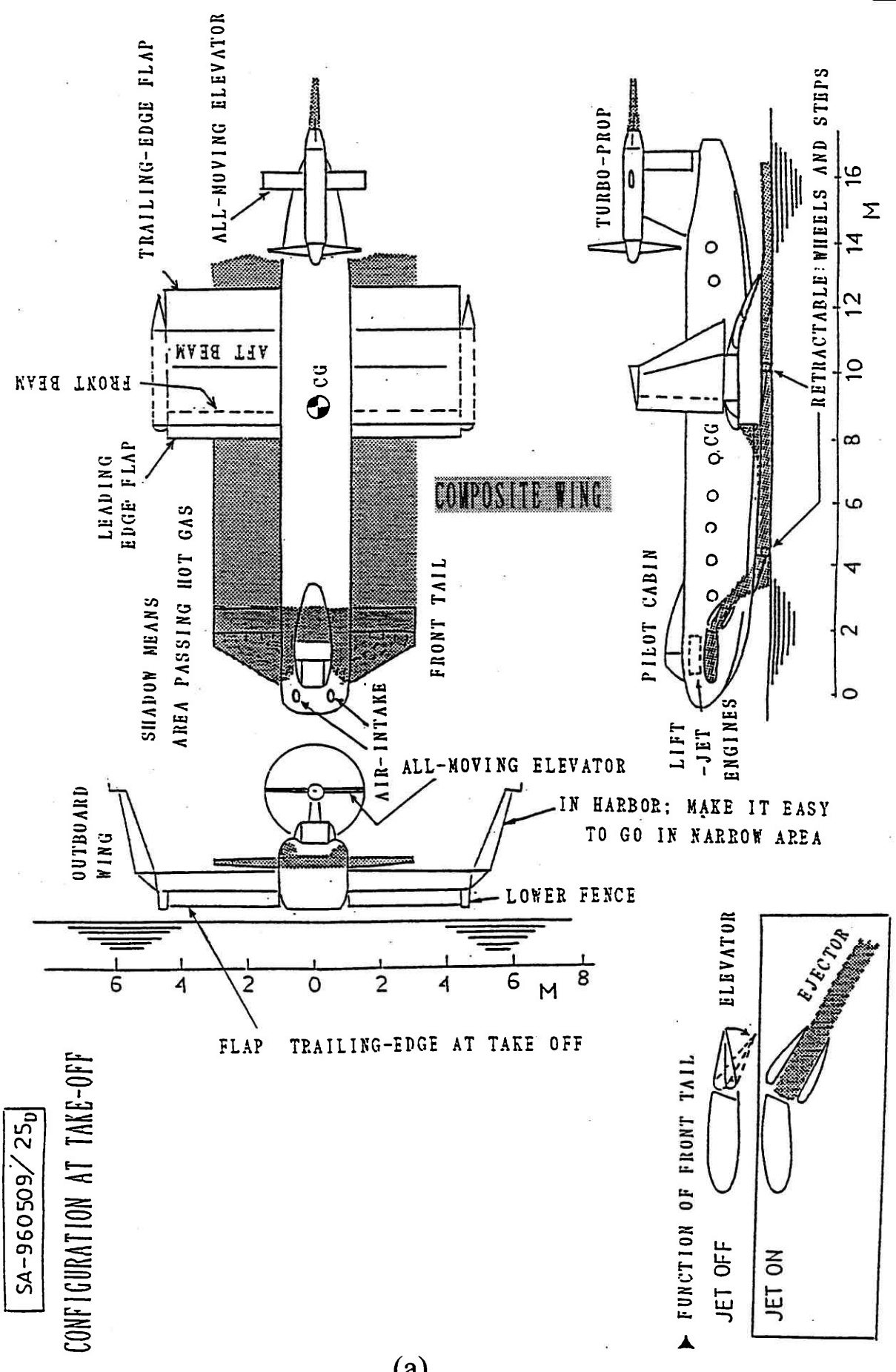


(a) The first.

Fig. 6 Values of output vs. PAS.

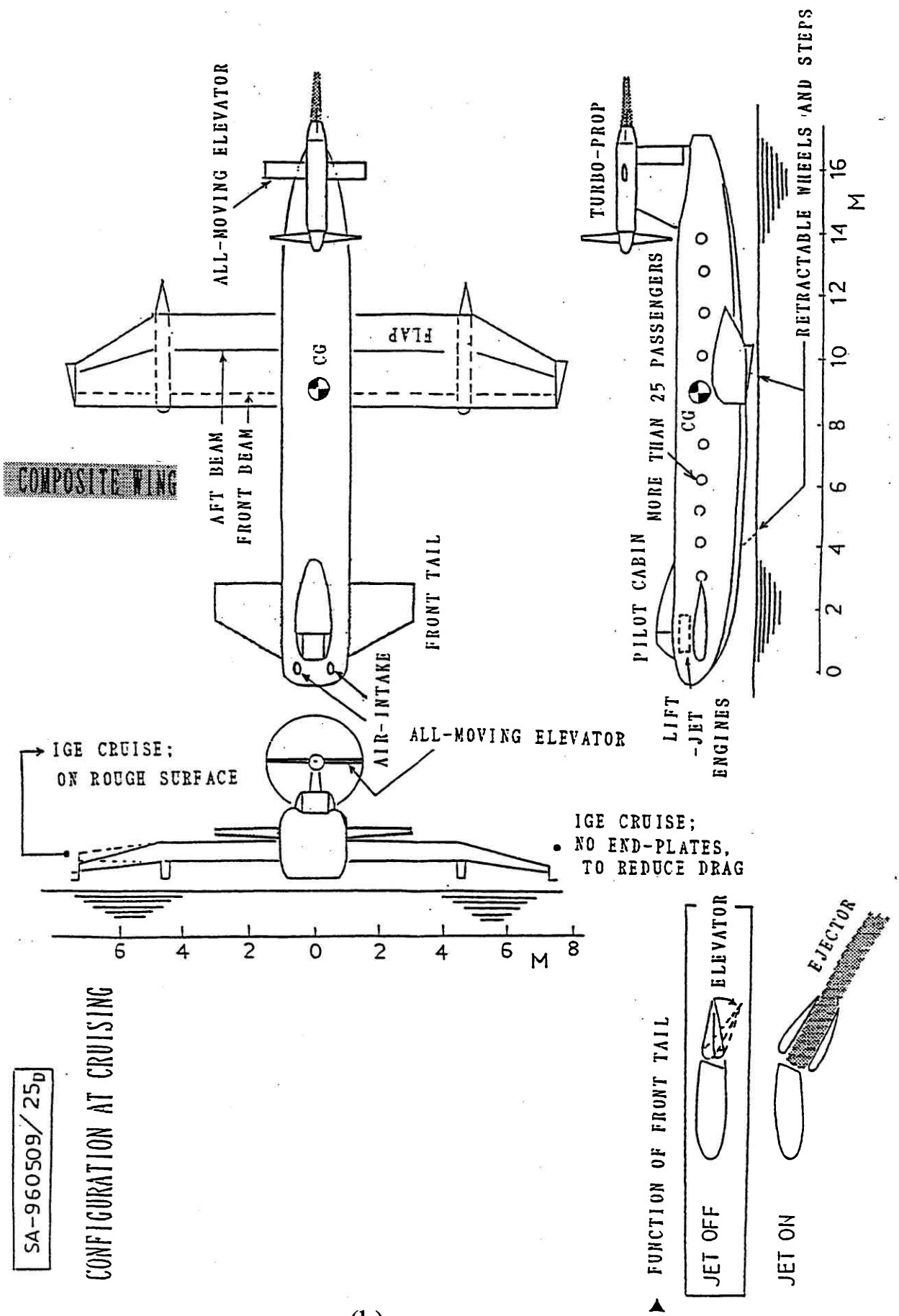

IGE CRUISE
AVERAGE IN YEAR
B/L
1.
.8
.6
LIFT/DRAG
50
40
30
20
10
0
15
10
5
(N·L/D) AVERAGE IN YEAR
1
5
25
125
625
PASSENGER NUMBER PAS

(b) Continued.



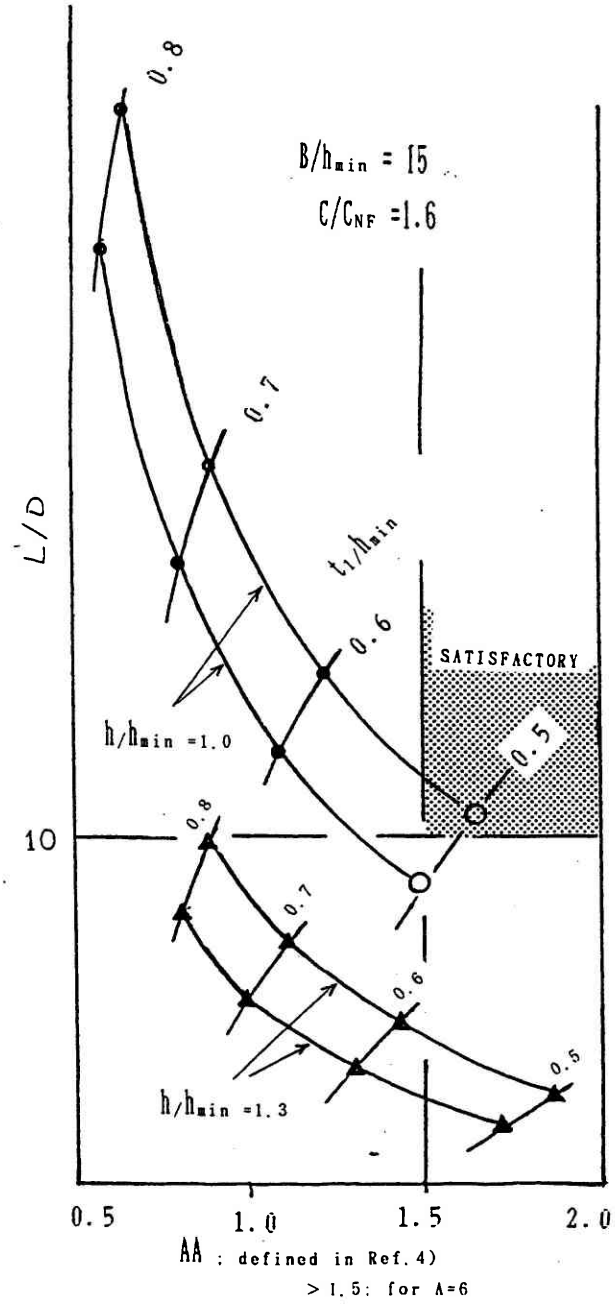
(a)

Fig. 7. A new WIG concept of 25 passengers, designed by the author



(b)

Fig. 7. A new WIG concept of 25 passengers, designed by the author



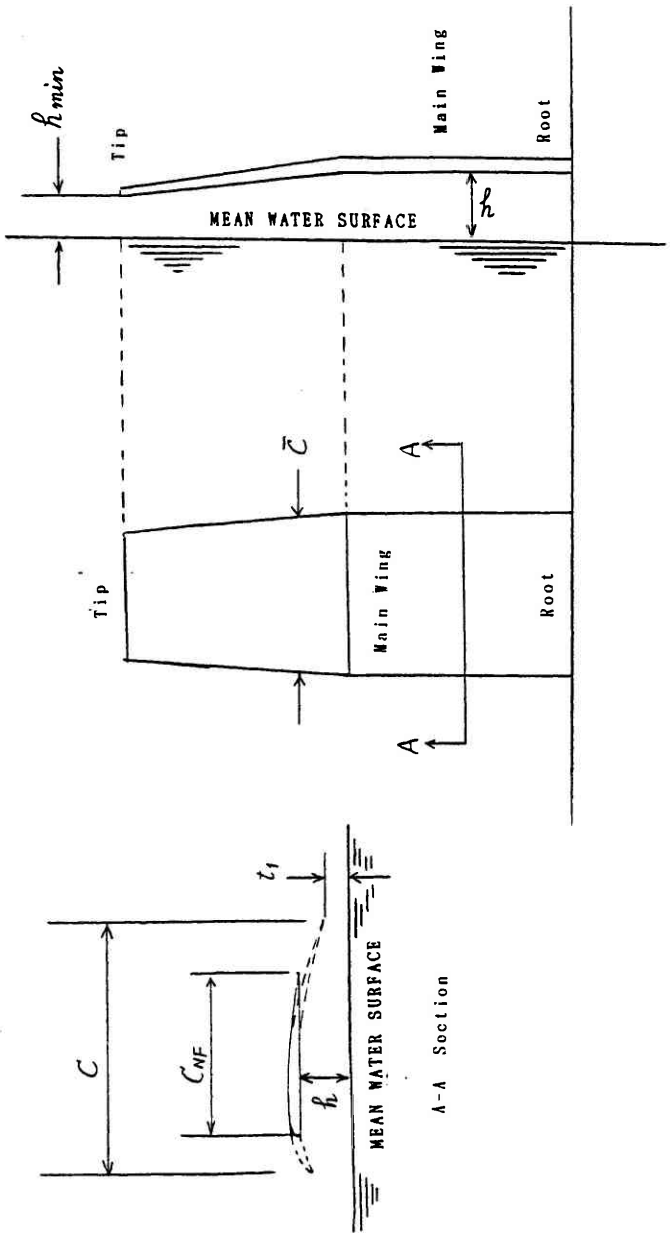


Fig. 8 Main wing geometry needed for satisfactory PAR effect at take-off and landing, if A=6 is wanted.

UTIAS Research on the Dynamics of the Bag and Finger Air Cushion Vehicle Skirt

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ABSTRACT

This paper reviews theoretical and experimental investigations of the dynamics of the bag-and-finger air cushion vehicle skirt undertaken at the authors' Institute. To facilitate analysis from first principles, the investigations use a two-dimensional section of the skirt moving in pure heave and subject to long-wave disturbances. Following successful completion of a theoretical and experimental investigation of the heave statics of a small model, a nonlinear mathematical model of the heave dynamics has been formulated. Numerical results suggest that characteristically nonlinear phenomena such as period doubling and chaos can be expected to occur during the normal operation of air cushion vehicles. Furthermore, a configuration representative of a 37 tonne vehicle shows a resonance associated with the skirt mass at frequencies in the range for which humans are most sensitive. Results from a linear analysis suggest that reducing the skirt mass may considerably ameliorate this effect. The linear analysis is also used to investigate the effects of cushion air compressibility on heave frequency response; significant effects are observed at frequencies associated with the skirt resonance, with the effect becoming more pronounced as a result of the reduction of cushion flow rates characteristic of modern designs. The role of dynamic fan effects is investigated by the applying a measured frequency response scaled from a small laboratory fan. Dynamic fan response appears to have only a small effect on the craft and skirt response, but may play a significant role in the dynamic instability leading to skirt bounce. The paper concludes by commenting aspects still requiring investigation.

INTRODUCTION

The successful development of the amphibious air cushion vehicle (ACV) is due in large part to the use of flexible skirts, which enable such vehicles to negotiate relatively large obstacles or waves while keeping lift air flow and power at moderate levels. A skirt may be defined as a collapsible structure, constructed from an elastomer-coated fabric composite material, which is inflated and stabilized by the cushion air pressure. Generally, skirt designs fall into two types: *responsive* and *non-responsive.* Responsive skirts usually undergo large geometric deformation in overall shape in response to inputs, even when the behaviour of the skirt material is inelastic[1]. On the other hand, except in the immediate neighbourhood of regions of surface contact, non-responsive skirts allow relatively small deformation, since such deformation occurs mainly as a result of material strain.

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The foremost example of a responsive skirt is the *bag-and-finger skirt* shown in Figure 1; developed initially in Britain, it is the type currently in use for most large ACVs[2]. A second and less widely used responsive skirt, also developed in Britain, is the *loop-and-segment skirt*. From a dynamical point of view, this skirt may be viewed as a limiting case of the bag-and-finger skirt in which the part of the bag immediately above the fingers is removed to make the air pressure in the bag the same as in the cushion. Operationally, however, there are other differences. Other variants of the bag-and-finger skirt include the *bi-bag* finger skirt developed in Russia[1], and the *bag-pericell* skirt developed in the United States[2].

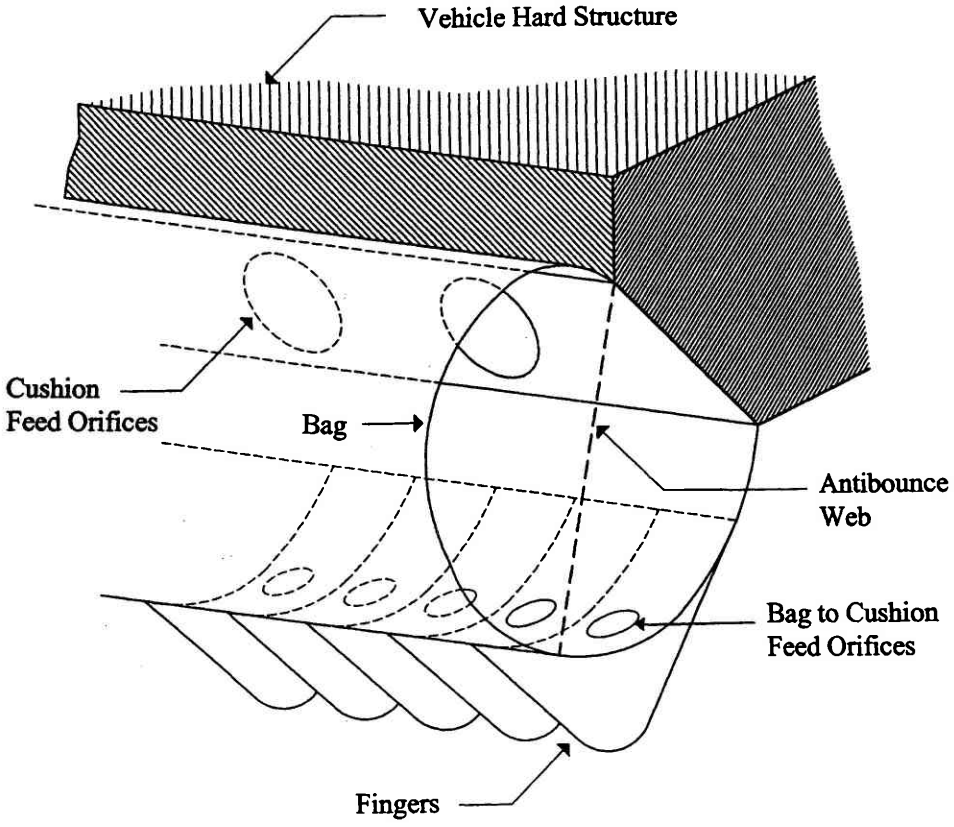


Figure 1 Main elements of the bag-and-finger skirt. Interior compartmentation, not shown, is used to provide pitch and roll stability.

Examples of non-responsive skirts include the *multicell skirt* developed in France, and the *uncompartmented-segmented skirt* developed in Canada[3]. The multicell system consists of several slightly-tapered, inverted truncated cones, with the number of cells determined by payload and stability requirements. The uncompartmented-segmented skirt, which is a variant of the loop-and-segment skirt, is used for low speed operation applications. The filtering function of the bag or loop is eliminated in this case and, to offset the reduction of the footprint area associated with elimination of the loop, a knee is included as part of the segment geometry.

Since their introduction in the 1960's, skirts have been developed mostly on an empirical basis, and there are basic questions concerning the dynamics of these systems which are still not understood. To cite but one example, Graham and Sullivan undertook a detailed investigation of the pitch-heave

dynamics of the uncompartmented-segmented skirt and, following comparison of their predictions with results obtained from a large model, they concluded that there are significant unidentified sources of skirt damping apparently associated with viscoelastic skirt material effects [4]. In this regard, although the bag-and-finger skirt has undergone considerable development since its first use in 1962, its general behaviour is still not completely understood, and it is still not free of problems. One such problem is its tendency to produce a rough ride [5,6] and another is its susceptibility to an instability known as *skirt bounce*[7], which is a self excited limit cycle oscillation involving predominantly vertical motion of the entire skirt. The *anti-bounce web* depicted in Figure 1 is often included to suppress this bounce, but it limits the downward motion of the skirt, and thus interferes with its responsiveness.

Research on flexible skirt systems at the authors' Institute (UTIAS) dates back to early 1970s, when a series of theoretical and experimental investigations of the dynamical properties of various skirt systems was undertaken. Aspects investigated include: the effect of the viscoelastic properties of the skirt material on dynamic stability, the nonlinear effects of skirt-surface contact in shutting off the hovergap, and the effects of air inertia in supply ducting [8-12]. However, all these investigations used non-responsive skirts, such as a multicell cone or the uncompartmented-segmented system.

Now it is a formidable task to develop a realistic model of the dynamics of the bag-and-finger skirt. Its geometry is complex, and can undergo large changes during vehicle motion. Being constructed from elastomer-coated fabrics, the viscoelastic properties of these materials can play a role in skirt dynamics [4,11]. Furthermore, to adequately model the cushion air escape process, the model must account for intermittent skirt-surface contact around the craft periphery arising from both craft motion and wave action; this can have major effects on the dynamics [12]. It follows that the development of tractable analyses from first principles requires considerable simplification. In this regard the first published analyses used empirical data on skirt deflection [13-15]. An analysis of the bag-pericell skirt assumed the bag to be rigid [16].

To allow consideration of bag dynamics, Ma and Sullivan proposed investigation of the configuration depicted in Figure 2; this is a two-dimensional section of the skirt constrained to move only in heave and subject to pure heave or long-wave inputs [17]. They used a Newtonian model to formulate a multiple-degree-of-freedom model of the skirt, and obtained useful preliminary results such as suggesting that, for most purposes, the skirt mass could be lumped in the fingers. Subsequently they developed a Lagrangian technique which eases the burden of including inputs to the skirt dynamics from the bag and cushion pressures [1]. This paper describes the theoretical and experimental work that has since been undertaken at UTIAS on this configuration.

CONFIGURATION USED IN INVESTIGATIONS

In the configuration of Figure 2, the vehicle or hard structure dynamics is described by the height $h_c(t)$ of the vehicle base above a datum, and the surface input is described by a specified ground height $h_g(t)$. Then, with h_s being the skirt height, and with h_e being the hovergap, or distance between the bottom tips of the fingers and the ground,

$$h_g + h_e + h_s = h_c \tag{1}$$

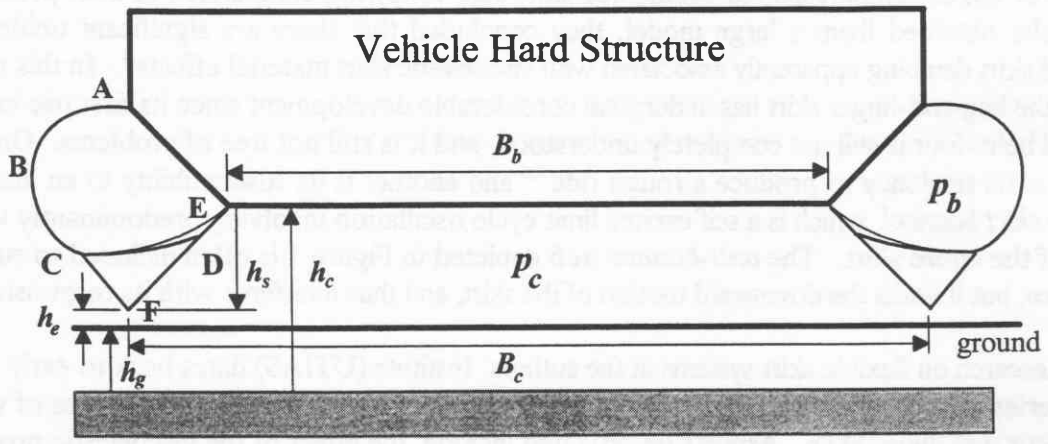


Figure 2 Configuration used for investigations

The analysis also allows for the possibility that the skirt contacts the ground, corresponding to $h_e < 0$. When this occurs we assume that only those parts of the finger forced into contact with the surface collapse, with the balance of the finger remaining fully inflated. This behaviour is observed in our laboratory models in motion over solid surfaces [4]; furthermore, for full scale vehicles travelling over water in the planing mode, the water inertia is high enough to cause finger collapse as if it were encountering a solid surface. Thus, when $h_e < 0$, for calculating both pressure forces acting on the fingers and cushion footprint area, the finger geometry is taken as that above the intersection of the uncollapsed finger and the ground-plane.

The lateral motion of the skirt in response to the surface input can be important, since this modulates the cushion footprint area. As depicted in Figure 2, with x_s being the lateral position of the skirt hemline and B_b being the width of the vehicle base between bag attachment points, the total width of cushion footprint B_c is thus given by

$$B_c = B_b + 2x_s \qquad (2)$$

EXPERIMENTAL MODEL

Figures 3 and 4 show the main features of the model used in the static experiments. It is a section of the skirt system hovering over a table (1), both being enclosed between transparent plastic end-plates (2) held in place by tie-rods (3). The end-plates permit observation and measurement of skirt deflections relative to the craft. The model's hard structure is a wooden box approximately 1.0×1.0×1.0 m ; this box is constrained to move in heave by linear ball bearings (5) which minimize frictional effects. An elastomer-coated fabric material is used for the skirt; both the bag length and the location of its inner attachment point (9) can be changed.

Air is supplied to the model from a variable speed centrifugal fan, through a circular duct (10) and a flexible, rolling seal (11) to a plenum box (4). The baffle plate (12) is placed in the box to eliminate the dynamic head of the air entering from the duct. The air flows into two bags (6) through

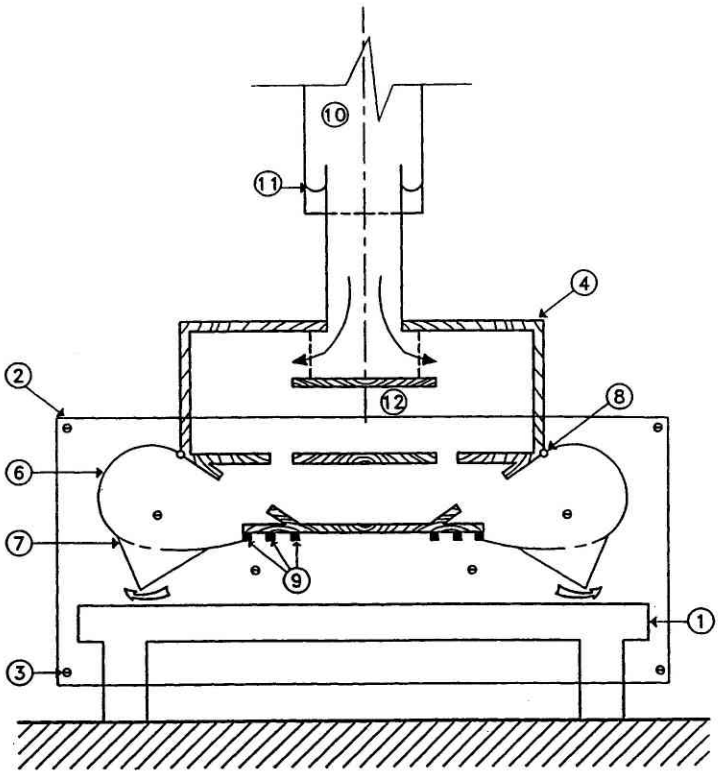


Figure 3 Cross-sectional view of the experimental model

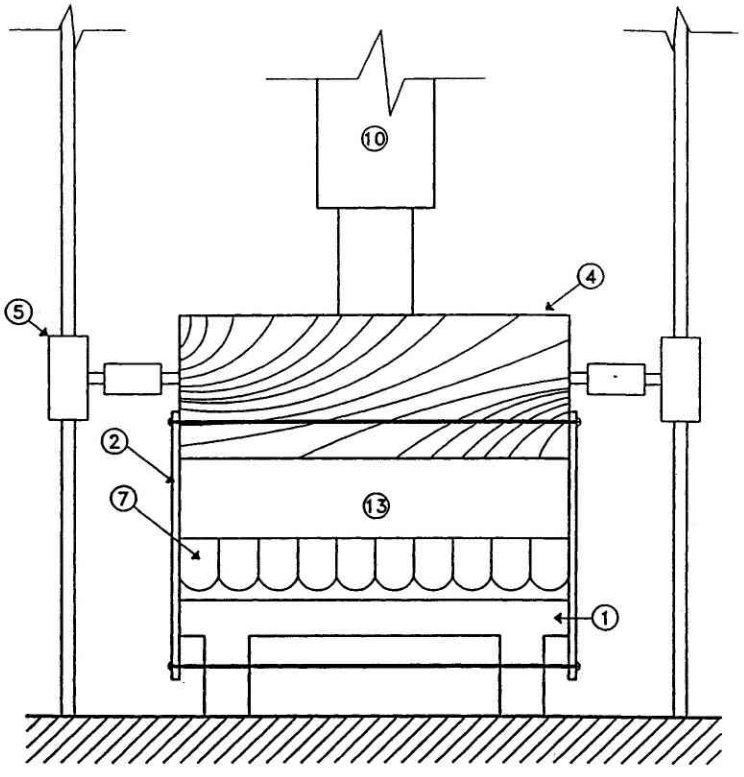


Figure 4 End view of the experimental model

three large holes in each side of the model, and from there to the interior of the fingers (7). Finally, the air escapes into the atmosphere between the bottom tips of the fingers and the table. The air flow rates delivered to the experimental model are determined by measuring the static pressure drop through the fan inlet. The model can be raised and lowered by a system of pulleys containing a load cell which measures the associated lifting force.

MATHEMATICAL MODELS USED IN THE ANALYSIS

Ma and Sullivan proposed several models to be used within their Lagrangian formulation, each involving different assumptions about bag geometry and behaviour. These models include: the *two-degree-of-freedom* skirt; the *single-degree-of-freedom*-skirt; and the *rigid skirt*. The effects of skirt material properties and sliding friction between skirt and surface are omitted, so that the skirt material influences the dynamics only through geometric shape change. Also, since the primary objective of our work is to examine the effect of skirt responsiveness, the anti-bounce web is omitted. The models are assumed to be symmetrical with each element of the skirt moving only in planes parallel to a cross section of the model. Each of these models is now considered in turn.

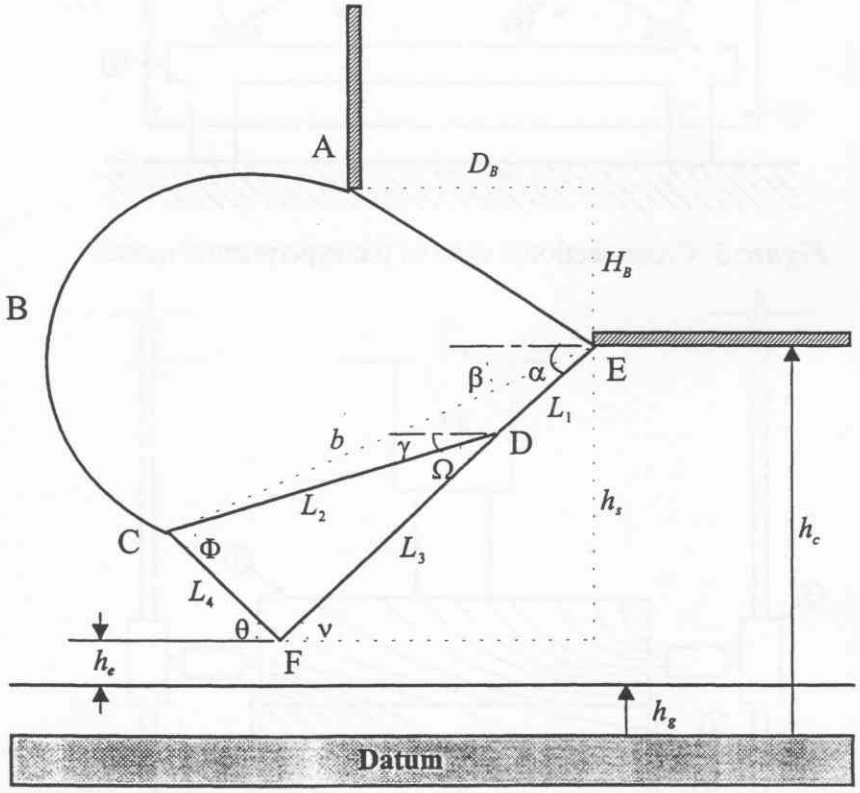


Figure 5 Elements of the two-degree-of-freedom model

Figure 5 depicts the main elements of the two-degree-of-freedom model. It comprises three distinct parts: the first is the *outer bag*, which is the part *ABC* of the skirt between the upper attachment point *A* and the outer edge of the fingers, *C*; the second is the *inner bag CDE*, and the third is the *fingers CDF*. The outer bag is assumed to be a massless inelastic membrane subject to a spatially uniform bag pressure p_b, so that it is always a circular arc. The inner bag is assumed to comprise two rigid massless links having lengths L_1 and L_2 respectively. With p_c being the assumed

spatially uniform pressure in the cushion volume V_c, these links are subject to the pressure difference $p_b - p_c$. The finger is assumed to be a rigid body having mass and moment of inertia attached to the link CD; the part CF is subject to p_c. The skirt has its mass concentrated at the centroid of the finger, and has two degrees-of-freedom corresponding to the angles α and γ defined in Figure 5.

The above model is called the *two-link* model to distinguish it from a second two-degree-of-freedom model known as the *two-membrane* model. As depicted in Figure 2, the latter model assumes the inner bag CE to be an inelastic circular arc membrane. The finger is attached to the bag at the point C, and to the craft base at E by a rigid link in such way that it does not touch the underside of the inner bag. For this model the inner bag is assumed to be a massless inelastic membrane which does not contact the upper edges of the fingers. Ma and Sullivan suggest that these two inner bag models encompass the behaviour of the skirt in practice [1]. Sullivan, Charest and Ma show that, at least as far as static response is concerned, there is little difference between the two models [18]. However, in the dynamics analysis, the two-link inner bag model was selected purely because it proved to be more convenient to express its dynamics in terms of mathematical equations.

The single degree of freedom skirt model, which is the simplest possible structural model of the skirt, assumes that a rigid finger and inner bag assembly rotates about point E; the inner bag thus becomes equivalent to a link of fixed length b which is at an angle β relative to the horizontal, and the outer bag is again assumed to be a massless inelastic membrane. In our calculations the two-link skirt model is converted to a single-degree-of-freedom skirt model by holding constant the angle $(\alpha - \gamma)$ between the links L_1 and L_2.

Finally, the rigid skirt model is a limiting case for the two other models in which bag deformation is prevented. This model is used to study the effect of the flexibility of the skirt by comparing its response with the that of the other two skirt models. Also it can be used to provide insight into the effect of an anti-bounce web since, as noted above, the main effect of such a device appears to be the limitation of vertical skirt motion. Furthermore, since our calculations for this model allow for the effect of finger-surface contact in the manner described above, this model can be used to represent the uncompartmented segmented skirt.

LIFT FAN CHARACTERISTICS

In an ACV the fans that deliver the lift air to the cushion must supply this air against a delivery pressure p_f which can fluctuate rapidly in response to modulation of the cushion volume by surface irregularities, and by craft motion in heave, pitch and roll. A common method of describing the behaviour of the fans is to assume that their response is *quasistatic*; that is, the flow Q_f through the fan is assumed to be a function of the pressure rise p_f across the fan and not of its rate of change. The pressure-flow relationship, referred to as the *fan characteristic*, can thus be obtained from a steady state test.

However it has long been known that, even at the relatively low frequencies characteristic of craft motion, significant deviations from quasisteady response can occur; some of the earliest data showing such behaviour was reported by Wheeler [19]. In the present work, to assess the significance of unsteady fan behaviour, the air flow Q_b from the vehicle lift fan into the bag is modelled in two ways: first, as a quasisteady response to the fluctuating bag pressure $p_b(t)$ by specifying a function of

the form $p_b = f_b(Q_b)$ representative of the steady fan characteristic; second, in order to show unsteady fan dynamic effects, by incorporating gain and phase shifts of Q_b with respect to p_b as a function of radian frequency ω as determined by using dimensional analysis to scale results from model tests on a small centrifugal fan [20]. This unsteady fan dynamic model is used only in the linear analysis.

Since direct determination of the true unsteady flow delivered by a fan is a difficult task Sullivan, Gosselin and Hinchey [20] proposed an indirect method based on the air cushion experiment depicted in the Figure 6. The fan being tested (1), together with its inlet and any downstream supply ducting delivers air to a rigid-wall plenum chamber cushion (2) which, in turn is mounted over a servohydraulically driven heave table (3). With the table oscillating at a preset frequency and amplitude, the histories of the cushion pressure $p_c(t) = p_f$ and the hovergap $h_e(t)$ between the lip of the cushion and the table are measured by transducers (5) and (6) respecively, and recorded. By assuming that the flow out of the cushion is quasisteady, the history of the cushion air escape flow $Q_a(t)$ is calculated, and the principle of conservation of mass applied to the cushion volume V_c to estimate $Q_f(t)$. This law includes both the effect of the varying V_c and its pneumatic capacitance.

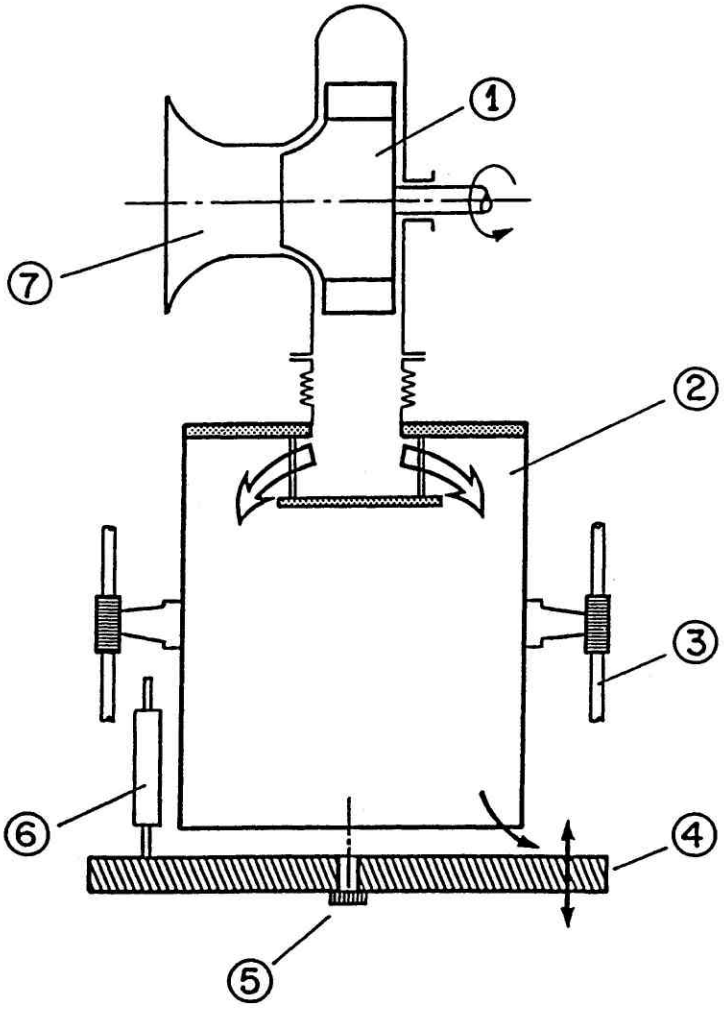


Figure 6 Modified air cushion heave dynamics experiment used to obtain dynamic fan response data

Tests were conducted on a small centrifugal fan having a rotor diameter $D_r = 0.330$ m and outlet width $B_r = 0.120$ m for fan speeds N_r in the range $2000 \le N_r \le 3000$ rpm. The table frequency f was in the range $0 < f < 12$ Hz, corresponding to reduced frequencies $f^* = f/N_r < 0.36$. Figure 7 compares the static characteristic for this fan with the mean response obtained during the dynamic tests in the form of a plot of $C_{FP} = p_f/(\rho_a N_r^2 D_r^2)$ against $C_{FQ} = Q_f/(N_r D_r^3)$. The curve is a polynomial fit to steady state data obtained by removing the plenum chamber and installing an orifice-plate flow meter, and the data points are the mean values of the measured p_f and computed Q_f histories averaged over the values of f used in the tests. With $j = \sqrt{(-1)}$, and with the fan response expressed in the form $H_{pQ}(f) = M_{pQ}(f) \exp[j\phi_{pQ}(f)]$, tests at selected frequencies showed that both gain M_{pQ} and phase shift ϕ_{pQ} are independent of the amplitude of oscillations in $h_e(t)$ for amplitudes up to 50 percent of the mean h_e. Both this amplitude independence and the agreement of the dynamic means with the static characteristic confirm that the fan response to the oscillations in p_f is linear.

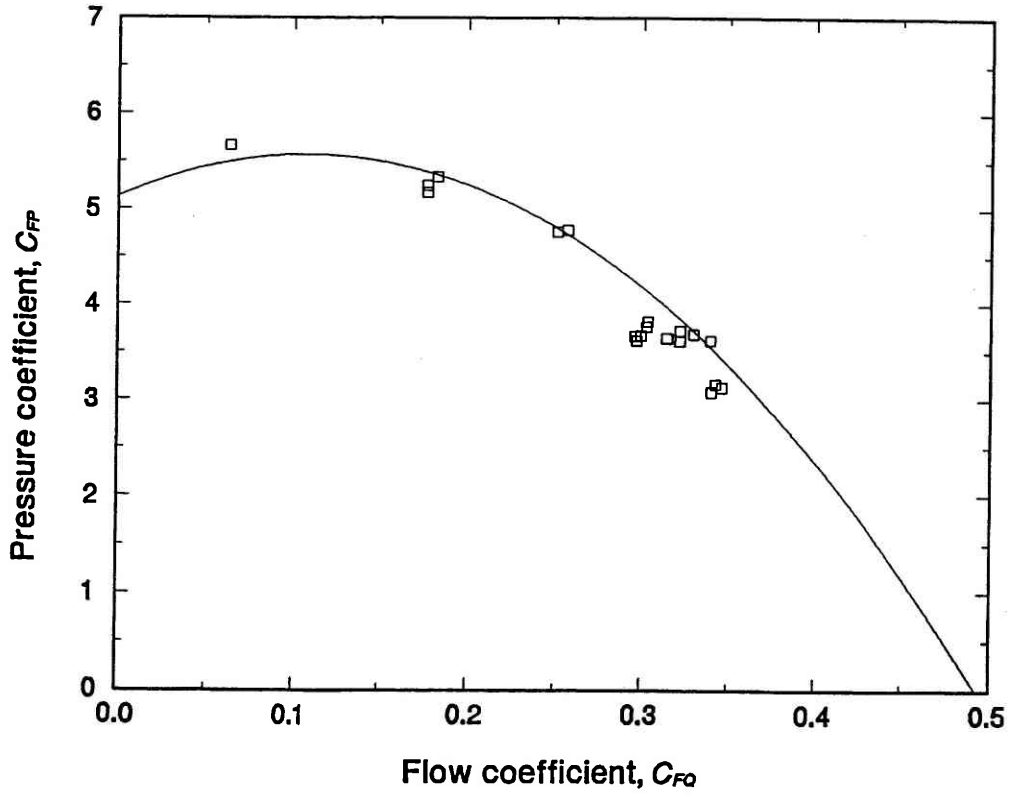


Figure 7 Comparison of fan dynamic test mean values of pressure and flow with static characteristic

Dimensional arguments suggest that, for a family of geometrically similar fans, if the dynamic response is linear, and if viscous effects can be ignored then, with $M^*_{pQ} = [(\rho_a N_f)/D_r]M_{pQ}$ being a nondimensional gain,

$$M^*_{pQ}\ ,\ \phi_{pQ} = fns(f^*, C_{FQ}) \qquad (3)$$

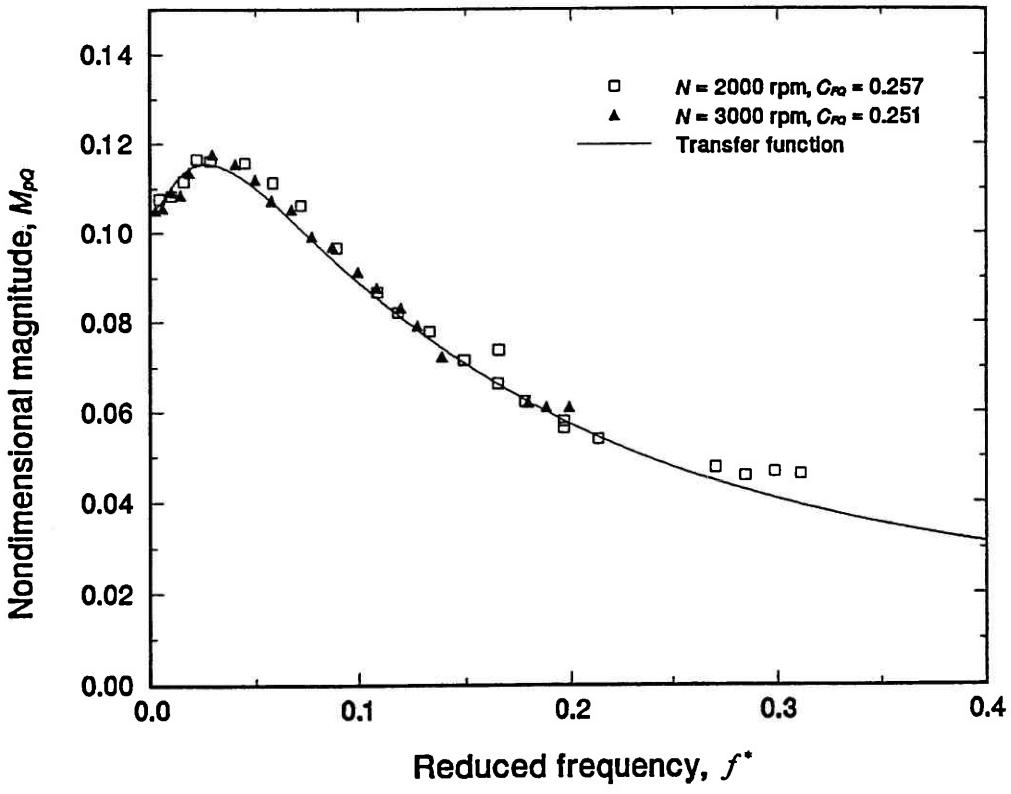


Figure 8 Effect of reduced frequency on nondimensional magnitude response of test fan

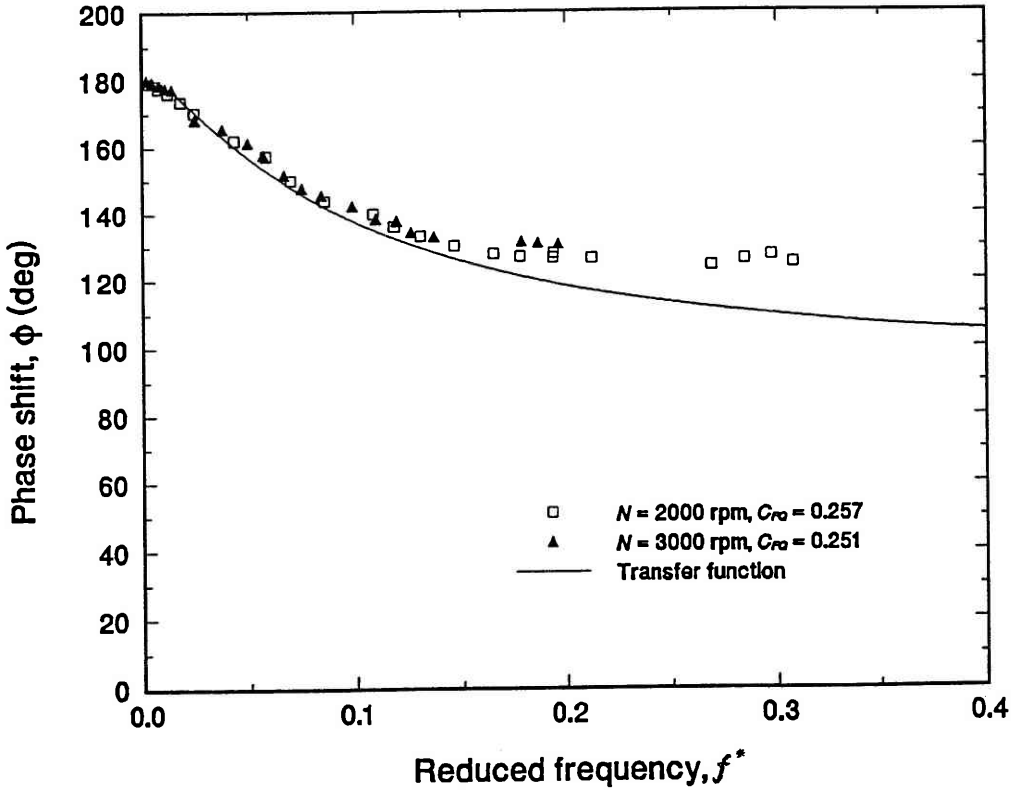


Figure 9 Phase response of test fan plotted against reduced frequency

To test this hypothesis Sullivan, Gosselin and Hinchey plotted M^*_{pQ} and ϕ_{pQ} against f^* for $N_r = 2000$ and 3000 rpm and for nominally the same C_{PQ} [20]. Figures 8 and 9 give this data; the close agreement supports the inference drawn from the dimensional analysis. This data is used to construct a frequency response function for use in the linear analysis; Figures 8 and 9 also show the fit of this function to the data.

AIR FLOW PROCESSES

The air flow Q_c from the bag to the cushion through the orifices in the inner bag, and that Q_a from the cushion to the atmosphere through the hovergap h_e shown in Figure 2 are assumed to be quasisteady and described by Bernoulli's law, together with suitable discharge coefficients [12]. The discharge coefficient for Q_a depends on the finger geometry through both h_e and the finger orientation angle θ which, as depicted in Figure 5, is the external slope of the finger relative to the ground. The discharge coefficient for Q_a can be replaced by an effective flow height h_f determined either analytically from the geometry of the segments, or experimentally. With B_f being the width of a single finger, Figure 10 compares typical computed and measured values of h_f/B_f obtained from the above laboratory model. The computation assumes an area available for flow equal to that between the fingers and the ground projected onto the vertical plane (shown in Figure 5), together with a discharge coefficient dependent on θ. The difference between the computed values and the data is caused by leaks at the end-plates of the model; this is not present in a full-scale vehicle. Figure 10 shows that, as h_e decreases from $h_e > 0$, h_f initially depends linearly on h_e; then, when surface contact occurs at $h_e = 0$, a further decrease in h_e causes h_f to decrease nonlinearly as the tips of the fingers (at F in Figure 5) collapse, shutting off the flow.

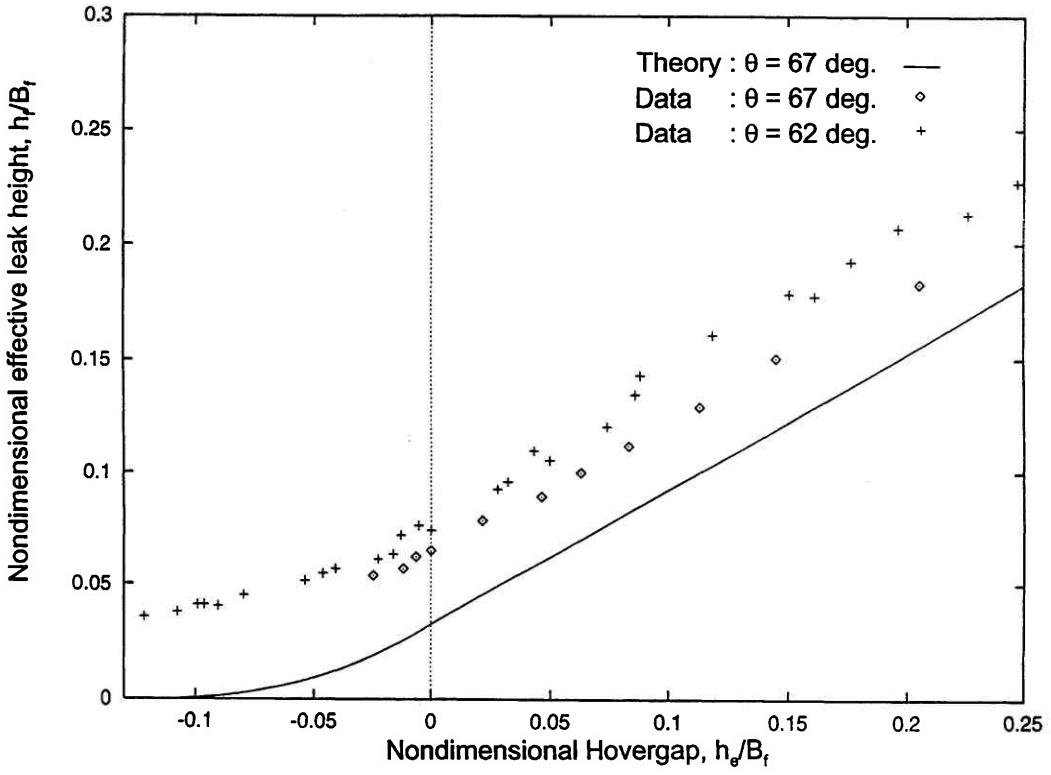


Figure 10 Predicted and measured h_f/B_f as a function of h_e/B_f

The bag and cushion volumes V_b and V_c are modelled as lumped pneumatic capacitances, this being included because the compressibility of the cushion air has been shown to significantly affect dynamics under certain operating conditions, and can be a source of dynamic instability [10].

NUMERICAL SOLUTION PROCEDURE AND VERIFICATION

The equations of motion of the skirt and craft are formulated using the Lagrangian technique devised by Ma and Sullivan [1]. The mathematical models of the system were translated into a computer source code and the system of equations was then solved for surface inputs of the form

$$h_g(t) = h_{g0} + h_{g1}(t)\sin(\omega t) \tag{4}$$

where h_{g0} is the surface input in the equilibrium state, h_{g1} is the amplitude, and ω is the input radian frequency. Craft parameters such as cushion equilibrium flow rates Q_e and bag-to-cushion pressure ratio were chosen to be representative of typical vehicle design conditions, and the values of ω and maximum h_{g1} were selected to be representative of typical operating conditions [21, 22]. Initial or equilibrium hover conditions were calculated by solving equations for the craft hovering statically with no ground input ($h_g = 0$). Then the time-domain motion responses were predicted by solving the differential equation of motions for the specified $h_g(t)$, with the computations being continued over a sufficient number of surface oscillations to allow the vehicle to settle into a steady state oscillation.

	Craft				Skirt						
Case	B_b (m)	L_b (m)	L_c^* (m)	M_c (kg)	L_1 (m)	L_2 (m)	L_3 (m)	L_4 (m)	L_{ob} (m)	M_s (kg)	Ω (rad)
Laboratory model	0.57	0.914	0.914	44	0.048	0.362	0.3	0.2	0.37	1.11	0.585
37 tonne craft	5.75	18.24	21	36,741	0.18	2.02	1.69	1.1	2.6	900	0.576

Table 1 Configurations used in simulations

	Flow				Skirt					Lift Fan	
Case	p_{ce} (Pa)	Q_e (m^3/s)	p_{be}/p_{ce}	h_e^* (m)	α_0 (rad)	γ_0 (rad)	H_c (m)	h_{f0} (m)	h_{s0} (m)	p_{br} (Pa)	Q_{br} (m^3/s)
Laboratory Model	411.3	0.59	1.7	0.009	0.591	0.012	0.205	0.012	0.195	800	0.59
37 tonne craft	2,016.5	96.8	1.2	0.004	0.501	0.187	1.258	0.028	1.254	2470	95.78

Table 2 Equilibrium conditions

Two cases were used in the numerical simulations: the first is the above laboratory model, and the second is representative of the 37 tonne CCG vehicle *Waban-Aki*. The configurations and equilibrium conditions used to represent these cases are given in Tables 1 and 2. The data are divided into several groups: the craft hard structure geometry, the skirt system geometry, the lift fan system data, and the cushion flow parameters.

The program was validated in two ways: (i) by comparison of its static heave stiffness predictions with measurements obtained from the laboratory model and, (ii), by comparison of the frequency response characteristics for small h_{g1} with those obtained from a separate linear analysis. Considering first the heave stiffness, Figure 11 compares computed and measured model mass, M_c, as a function of the equilibrium height H_c (i.e. h_c for $h_g = 0$), for the above laboratory model. The two-degree-of-freedom skirt model accurately predicts the static heave response of the bag and finger skirt, and the single-degree-of-freedom model provides comparable predictions. As expected, the rigid model predicts high heave stiffness, corresponding to large $|dM_c/dH_c|$. Figure 12 is an example of the effects of a skirt geometry change on cushion stiffness, with the predictions obtained using the two-degree-of-freedom model; it shows that outer bag length variations have little effect on the stiffness characteristics of the skirt. For all static stiffness cases examined, the agreements between prediction and measurement is virtually identical to that obtained by Sullivan, Charest and Ma,who solved the static equations directly, using a different computer program [18].

The verification of the dynamics predictions is discussed below in conjunction with the presentation of the results.

NONLINEAR DYNAMICS RESULTS

Numerical simulations of heave responses to waves of various amplitudes and encounter frequencies were performed. The vehicle parameters used in all the results presented below are for the 37 tonne configuration and, unless noted otherwise, the two-degree-of-freedom skirt model is used in the calculations.

For a surface input amplitude forcing skirt-ground contact (h_{g1} = 88 mm), Figures 13 and 14 show, respectively, the superposed h_c and p_c histories and the corresponding superposed p_c and Q_a histories. The peak in p_c, which is about four times the equilibrium value, occurs at the lowest h_c, and there are periods where $p_c < 0$. The Q_a history exhibits corresponding characteristics, including periods of flow reversal. Furthermore, the histories have considerable harmonic content; comparison with those obtained in the absence of skirt-surface contact show that this harmonic content is a direct consequence of surface contact. These predictions are consistent with observations made by Sullivan Byrne and Hinchey, who compared numerical predictions with experiments for a small plenum chamber cushion undergoing limit cycle oscillations involving skirt-surface contact [12]. In particular the p_c histories that they observed bear a striking qualitative similarity to those in Figure 13. It should be noted that the periods of negative p_c, which were also observed in these experiments, only occur during a small fraction of the motion cycle. Sustained negative p_c will cause the skirt to collapse, but we assume that the short time intervals for which $p_c < 0$, skirt inertia prevents this.

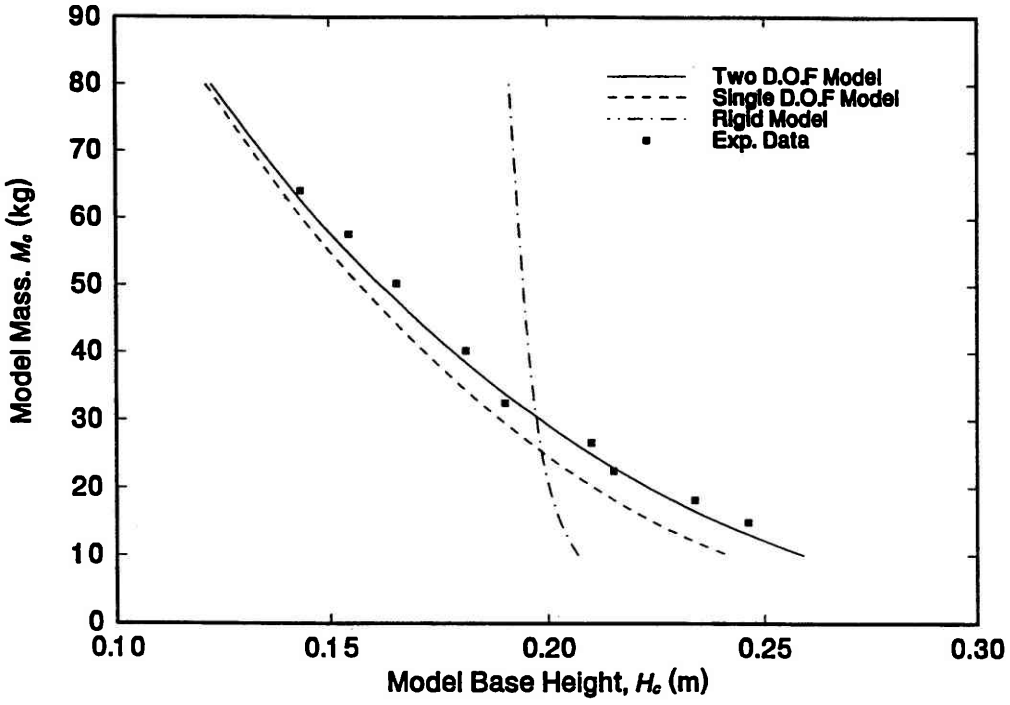


Figure 11 Predictions and measurements of static stiffness using different analytical models

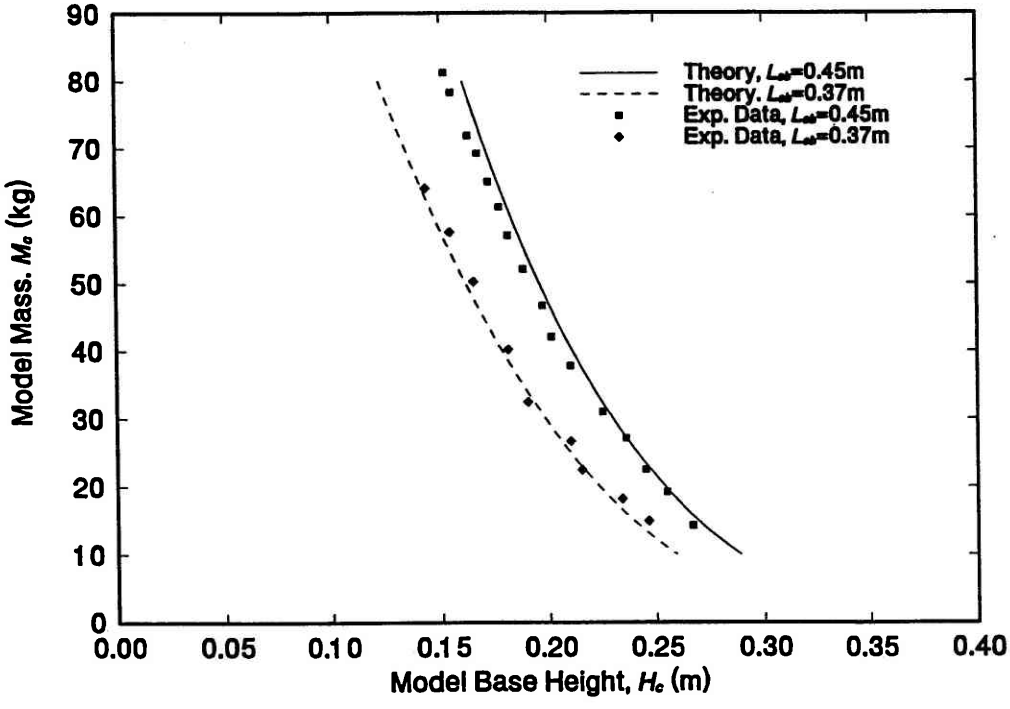


Figure 12 Comparison of prediction and measurement of effect of outer bag length on heave stiffness of laboratory model.

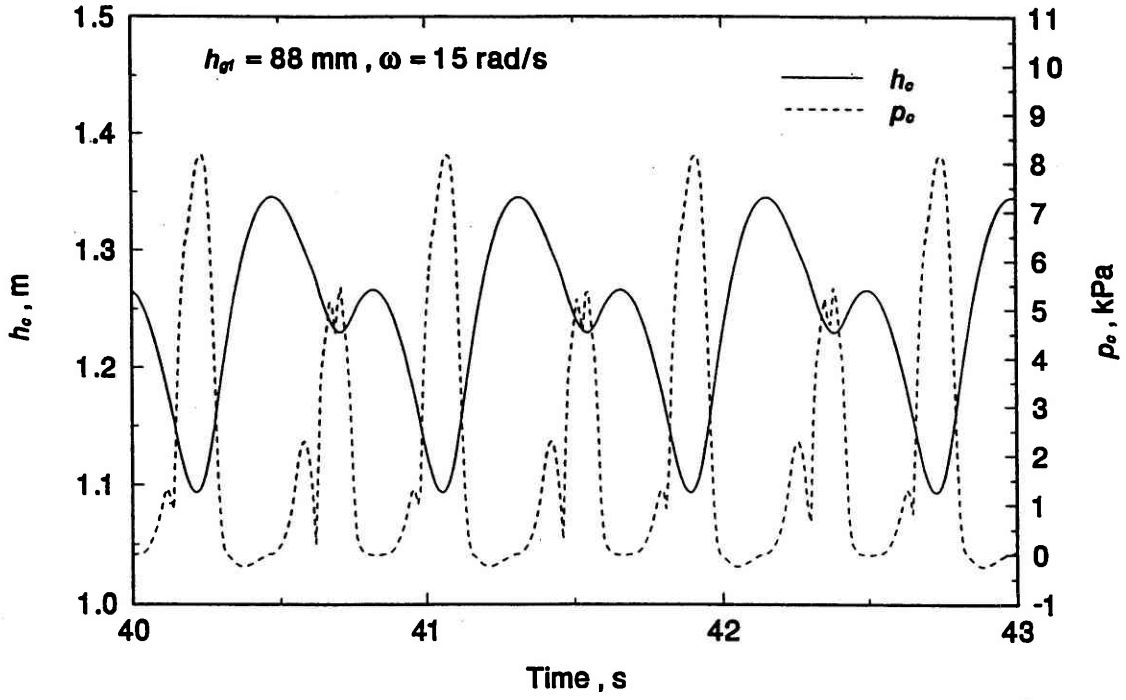


Figure 13 Typical predicted histories of h_c and p_c for oscillations involving skirt-surface contact; $h_{g1}/Hc = 0.07$

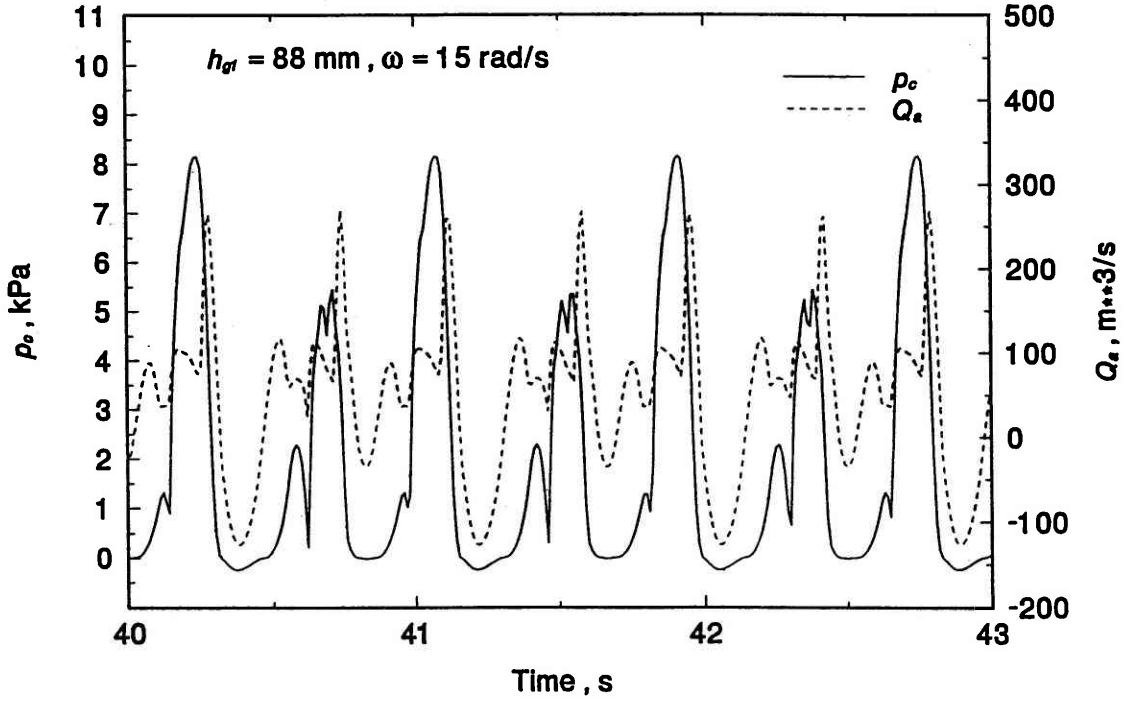


Figure 14 Histories of p_c and Q_a for the conditions of Figure 13

Figure 15 compares heave amplitude response with the predictions of the separate linear analysis. This shows a characteristic double-peak, with low frequency peak being associated with the craft mass, and the high frequency peak associated the mass of the skirt. For h_{g1} = 0.1 mm, the linear and nonlinear results are indistinguishable and, for h_{g1} = 1.0 mm, observable nonlinear effects occur only in the neighbourhood of the second resonance peak, which is at ω = 24 rad/s (3.94 Hz). The deviation from linear response in the neighbourhood of the 3.94 Hz. resonance is associated with the very large motion of the skirt interacting with the flow function nonlinearity depicted in Figure 10.

Figure 16 illustrates the effect at ω = 15 rad/s on $h_c(t)$ of slowly increasing the input amplitude h_{g1} in the range $0.01 \leq h_{g1} \leq 0.32$ m. This value of ω is high enough to involve ride comfort implications while avoiding the skirt mass resonance shown in Figure 15. Also, according to the normal operational limits expected for a 37 tonne craft, at ω = 15 rad/s, it can expect to encounter waves having h_{g1} as large as 0.32 m, corresponding to peak-to-peak wave heights of about 50 percent of H_c[21, 22]. To obtain these results, the duration of the interval over which the change in h_{g1} imposed was increased until the envelopes of the h_c histories were not affected when plotted against the linearly changing h_{g1}.

Even though skirt-ground contact already occurs for $h_{g1}/H_c > 0.001$, the graph in Figure 16 demonstrates essentially linear behaviour for $0 \leq h_{g1}/H_c \leq 0.022$; that is, h_{c0} remains constant and equal to H_c, and h_{c1} is very nearly proportional to h_{g1}. As h_{g1} increases further, the first significant nonlinear effect is an abrupt decrease in h_{c0}, followed by a period-doubling at $h_{g1}/H_c = 0.091$, which abruptly increases the amplitude of the craft heave motion by a factor in excess of three. Figure 17 gives the details of the transition. At $h_{g1}/H_c = 0.18$, $h_c(t)$ ceases to be periodic and the amplitude of the motion becomes erratic. When h_{g1} is decreased from its peak value, chaotic motion abruptly ceases at about the value of h_{g1}/H_c at which it first occurred, but period doubling dies out only when h_{g1}/H_c decreases to 0.061, a value significantly lower than observed in Figure 16. Examination of phase plane plots and Poincaré maps shows that the erratic behaviour has the characteristic features of chaotic motion.

For selected ω, Figure 18 plots a measure of the ratio of the amplitude of craft oscillations in $h_c(t)$ to h_{g1} against h_{g1}/H_c. Prior to the onset of period-doubling, the measure of the oscillation amplitude is the amplitude of the fundamental of $h_c(t)$ as determined by Fourier analysis and, at its the onset, the amplitude is taken to be one half of the peak-to-peak motion. In each case the plot terminates at a value of h_{g1}/H_c which we estimate to be the maximum likely to be encountered at the given ω. These plots suggest that, except in the neighbourhood of the resonance at ω = 25 rad/s., prior to the onset of period-doubling, the craft response is predominantly linear.

LINEAR DYNAMIC RESULTS

To obtain the frequency response results presented below, the nonlinear equations were linearized about an equilibrium point, and the resultant system of equations was expressed in state-space matrix form. Laplace transforms were then applied to this format and, with $s = \sigma + j\omega$ being the Laplace variable, the Laplace transform of the perturbation of a variable $x(t)$ is written as $\Delta x(s)$.

Figures 19 and 20 show the effect of the skirt flexibility on craft amplitude and phase response, with the rigid skirt response as a reference condition. The amplitude of the craft heave

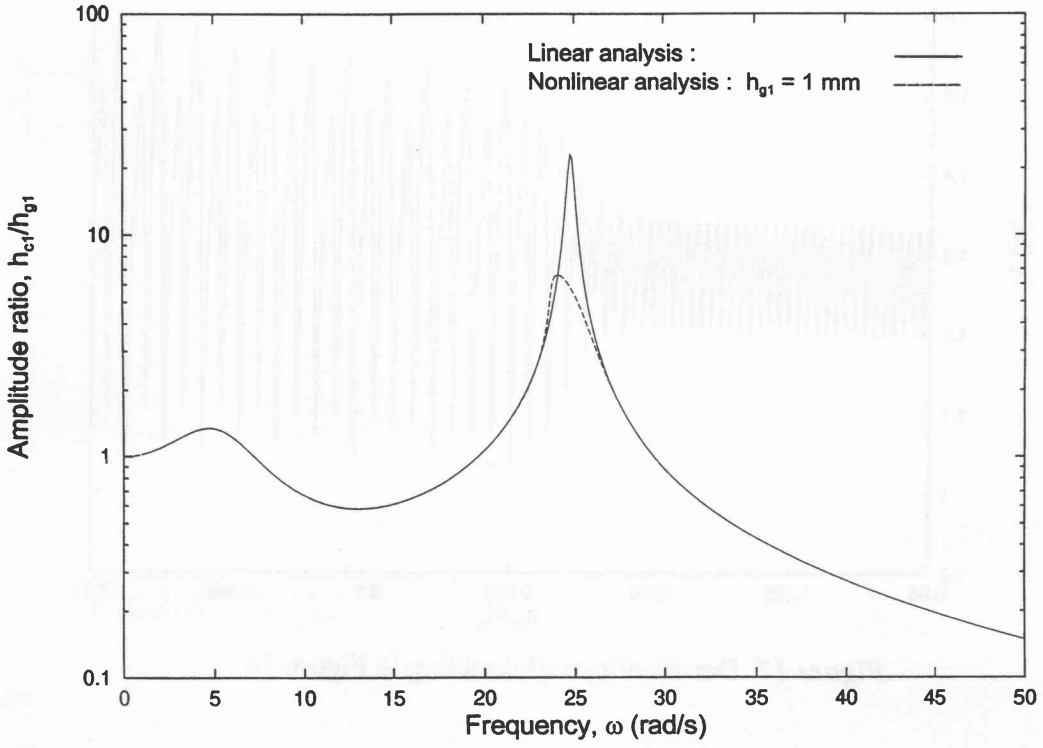


Figure 15 Comparison of linear and nonlinear heave amplitude response for the two-degree-of-freedom model and for h_{g1} = 1.00 mm, corresponding to $h_{g1}/H_c = 7.9\times10^{-4}$

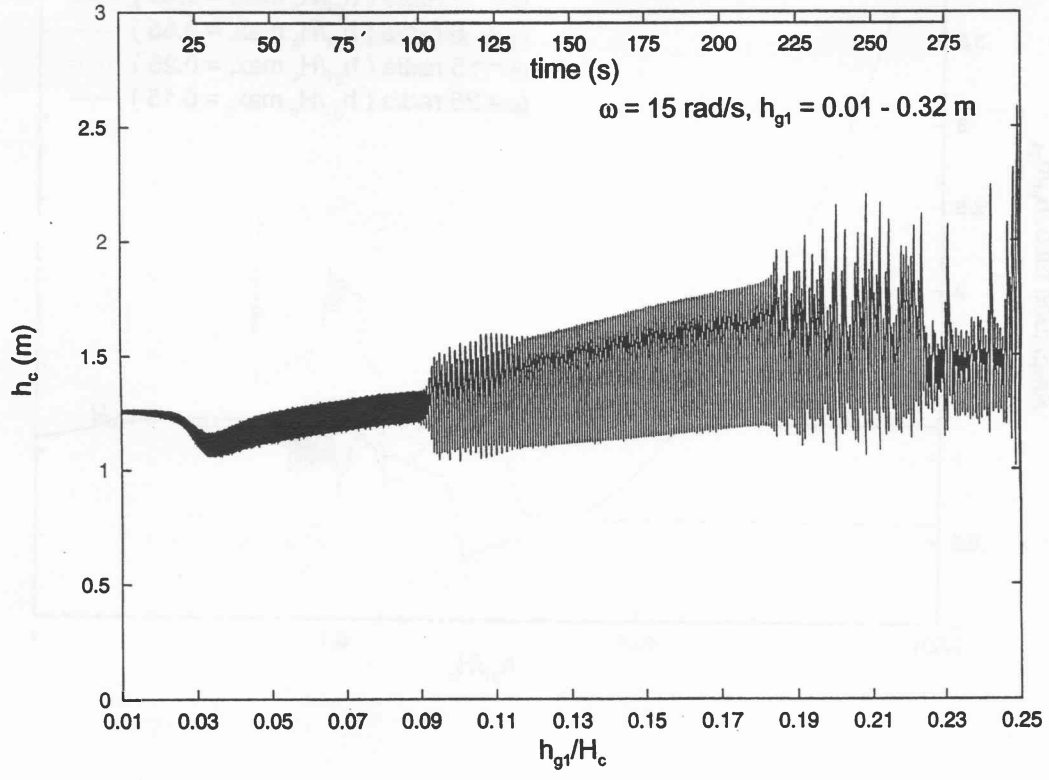


Figure 16 History of craft response to a slowly increasing surface input amplitude

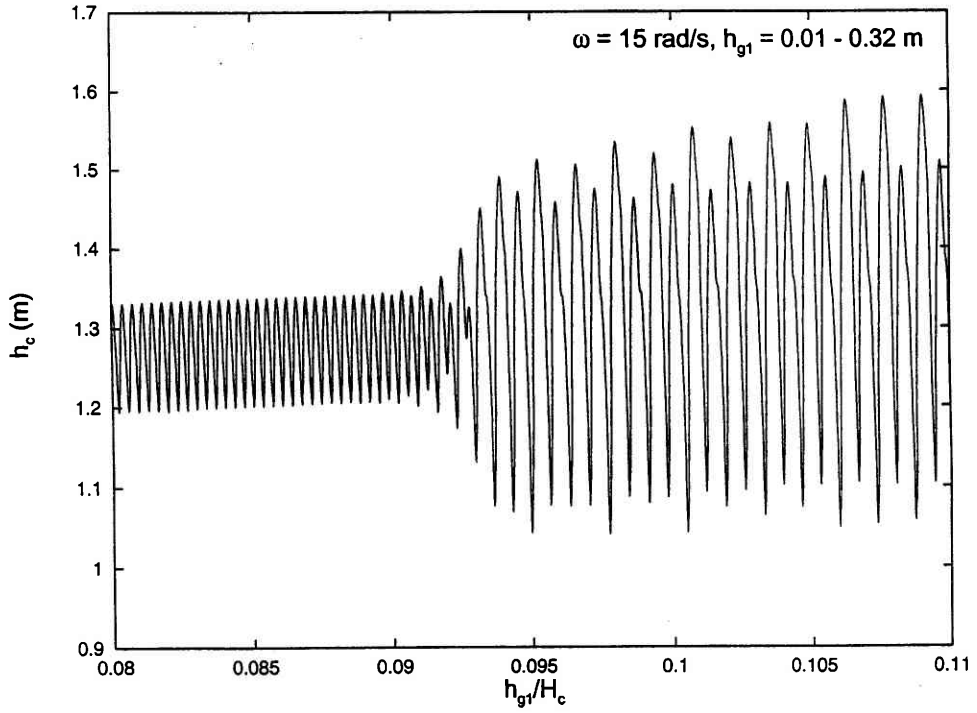


Figure 17 Details of period-doubling in Figure 16

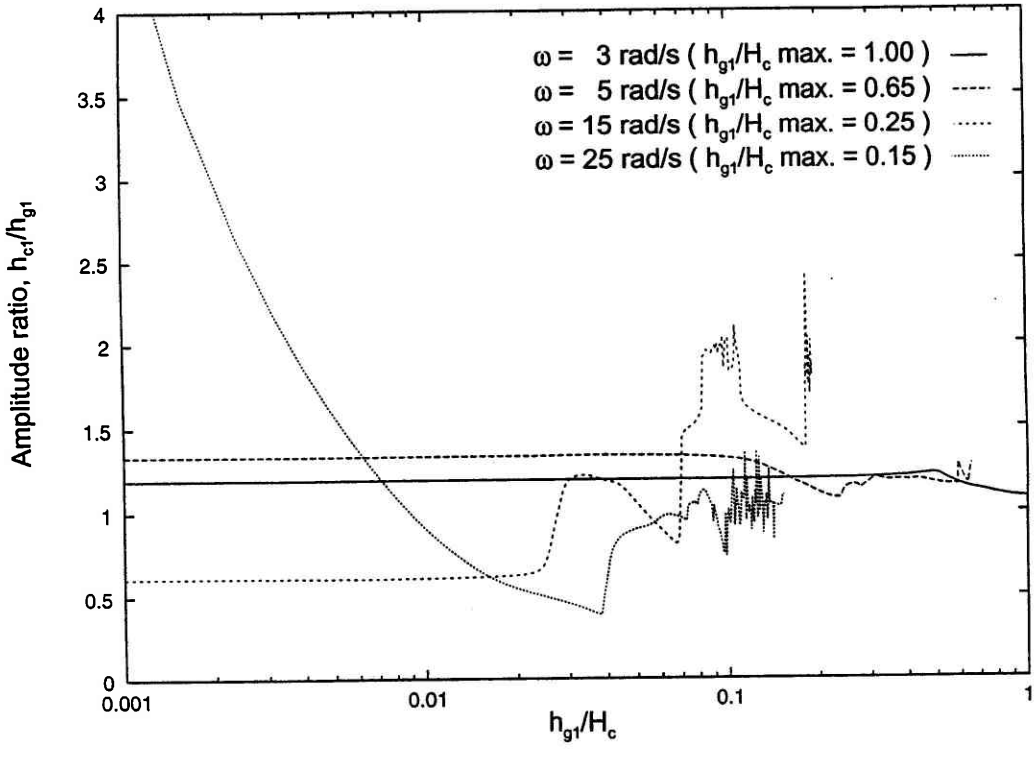


Figure 18 Effect of input amplitude on the response amplitude ratio for selected ω

frequency response $\Delta h_c(j\omega)/\Delta h_g(j\omega)$ shows the characteristic double-peak observed in the nonlinear results. Furthermore the results in Figure 19 also suggests that, at least for the configuration used in the present analysis, the ride comfort problem is not improved by using a skirt. Thus, because the resonance peak associated with craft mass moves from 16.5 rad/s (2.62 Hz) to 4.8 rad/s (0.76 Hz) the amplitude response is substantially reduced in the neighbourhood of ω = 13 rad/s (2 Hz). However, because of the flexibility of the skirt, a large resonance peak associated with the skirt mass now appears at 24 rad/s (3.94 Hz). Clearly this is undesirable, since humans tend to be most sensitive to this type of motion in the range 4 - 8 Hz [23]. Figure 21 shows the effect of reducing the skirt mass to one half and one fifth of the value given in Table 1 (from 900 kg to 450 kg and 180 kg). The effect on the first natural frequency is negligible, thus implying that this skirt responds as if it is inertialess for frequencies in this neighbourhood. But the response obtained by reducing the skirt mass not only increases this second natural frequency but it also greatly reduces the undesirable large resonance peak. This suggests that reducing skirt mass may be one way to improve ride comfort.

Figures 22 and 23 give the effects of the capacitance on craft heave amplitude and phase response. As the frequency increases, compressibility effects become increasingly significant, being negligible near the first resonance frequency, but are highly significant for the skirt bounce frequency. Capacitance thus reduces the frequency of the skirt mass resonance frequency while, at the same time greatly increasing its amplitude. Figures 22 and 23 also show the effect of capacitance on craft heave amplitude and phase response for two equilibrium flow rates Q_e. The lower value of Q_e corresponds to values currently used, whereas the higher value is typical of an earlier generation of vehicles [24]. This shows that decreasing Q_e increases capacitance effects, with the effect being particularly prominent in the neighbourhood of the skirt mass resonance. Decreasing Q_e improves craft heave response at low frequencies, since it gives a resonance peak which is lower than the high Q_e case, but it greatly increases the magnitude of the skirt bounce resonance. The results also suggest that, for very low frequency responses, capacitance may be omitted from the calculations. However, for lower Q_e, and for such problems as skirt bounce or high speed passage over short waves, it should be included, since the results show that low Q_e with compressibility may be detrimental to ride quality.

The results presented above assume quasisteady fan response, and thus do not include the effects of unsteady fan dynamics. Figures 24 and 25 show the heave amplitude and phase response for both quasisteady and unsteady lift fan behaviour obtained as described above. The response is only moderately affected by unsteady fan behaviour at low frequencies, but in the neighbourhood of the skirt resonance, major phase-shifts are introduced. This suggests that unsteady fan behaviour may have a major influence on system stability and thus on skirt bounce.

CONCLUSIONS

The nonlinear simulations suggest that characteristically nonlinear dynamical phenomena such as period doubling and chaos may be expected to occur during the normal operation of ACVs equipped with the bag and finger skirt, and that this may have significance for ride comfort. The linear analysis suggests that using a skirt does not necessarily improve ride comfort, and may actually make it worse. However, the results also suggest that reducing skirt mass may be one way to improve the problem. This in turn suggests that skirt response might be improved by using a modern high-strength light weight material to reduce mass except for those parts where wear due to surface contact may be expected. Air compressibility also affects heave response at high frequencies, with the effect being

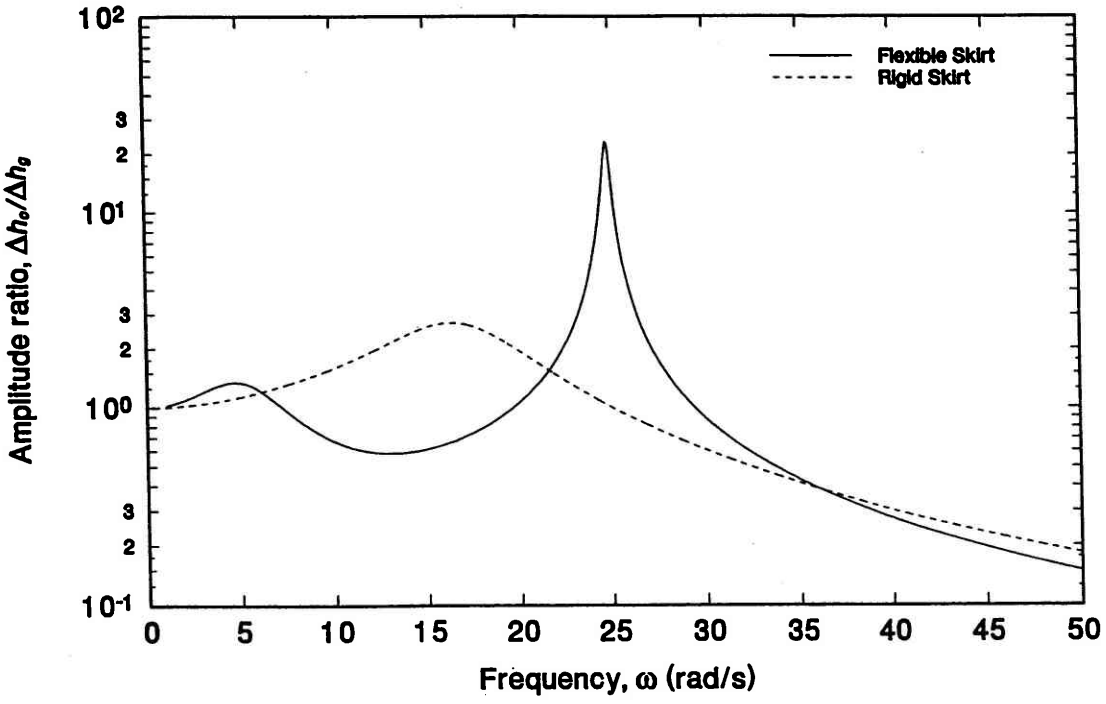


Figure 19 Effect of skirt flexibility on heave amplitude response

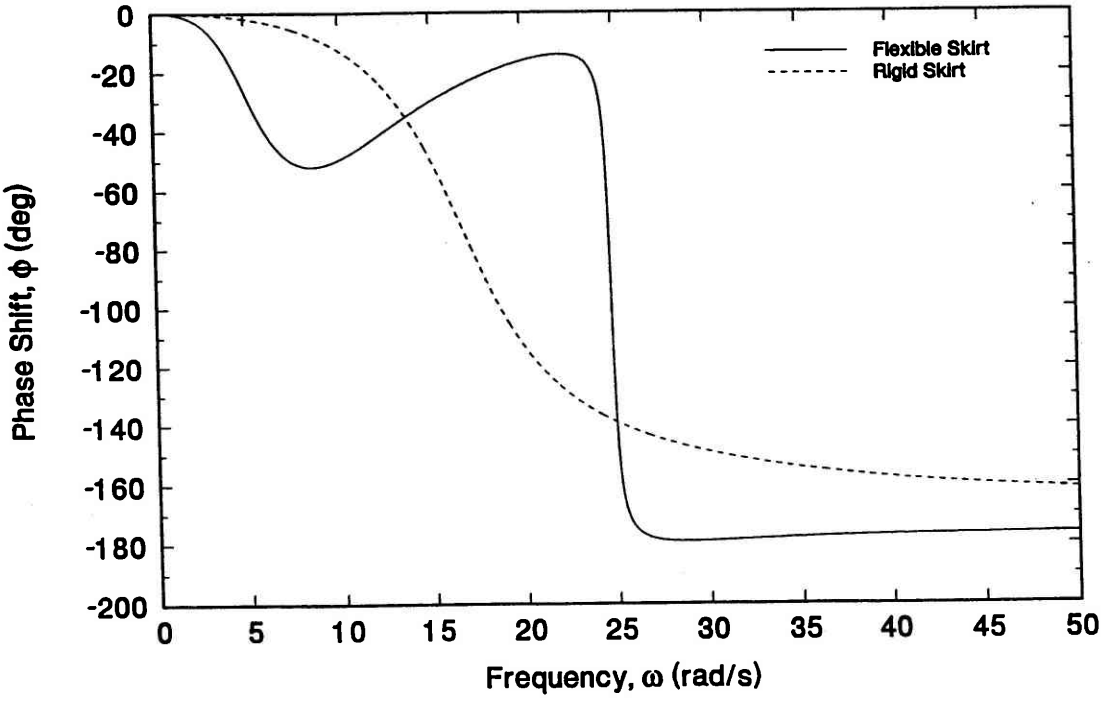


Figure 20 Effect of skirt flexibility on heave phase response

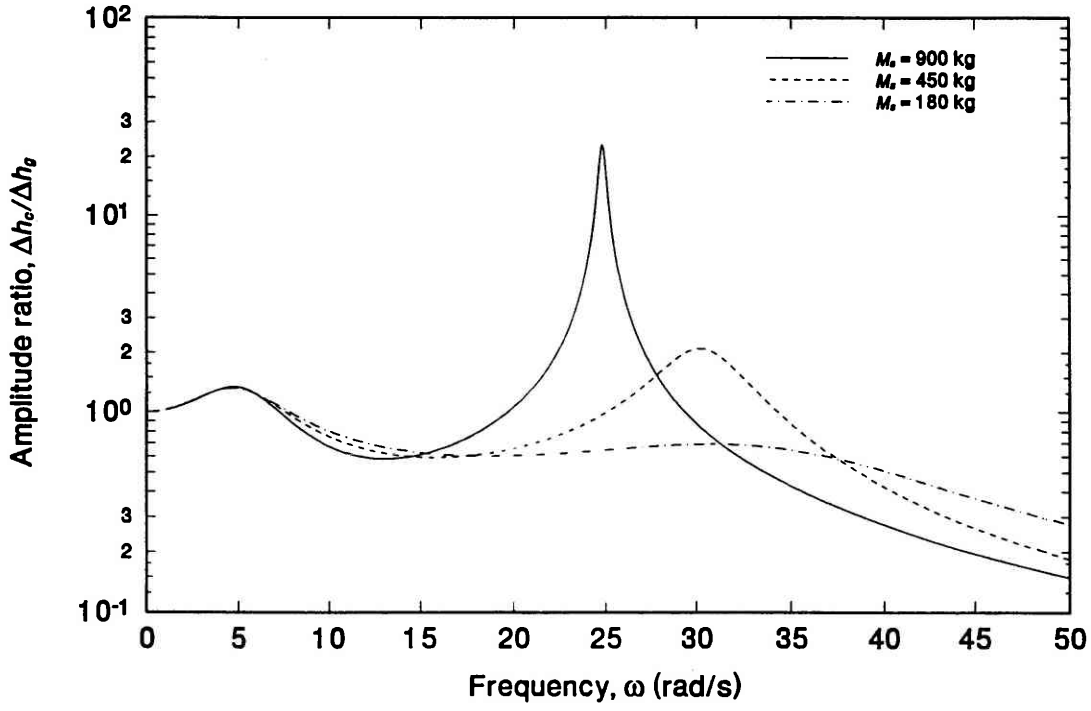


Figure 21 Effect of skirt mass on heave amplitude response

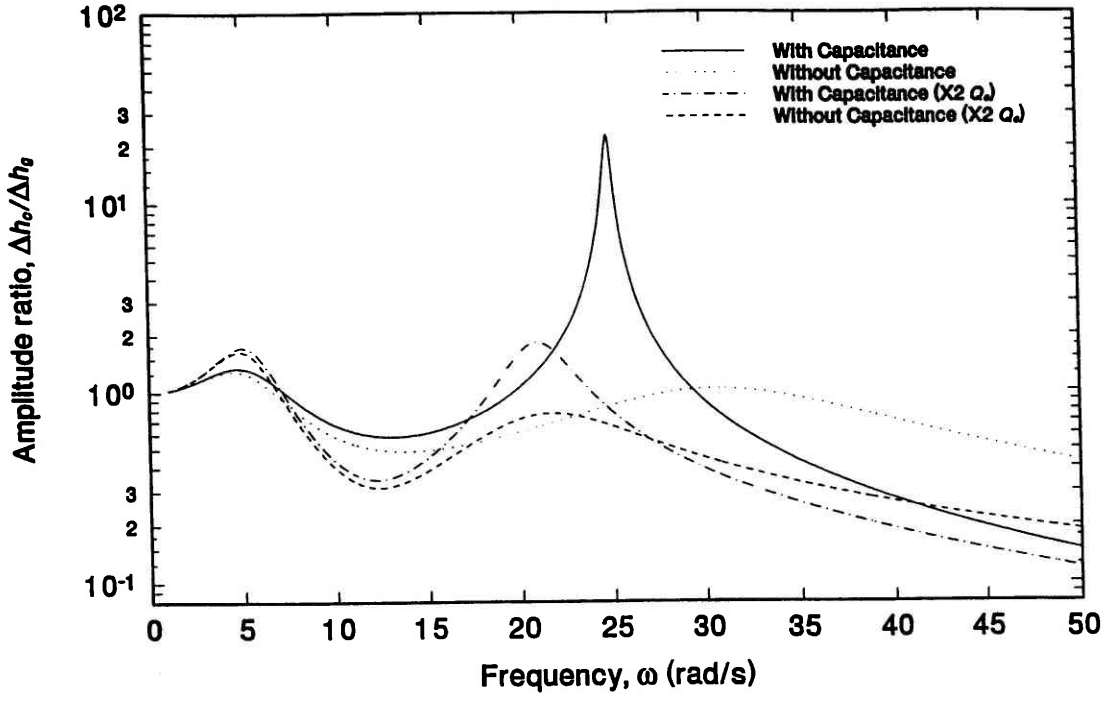


Figure 22 Effect of air compressibility on heave amplitude response for low and high flows

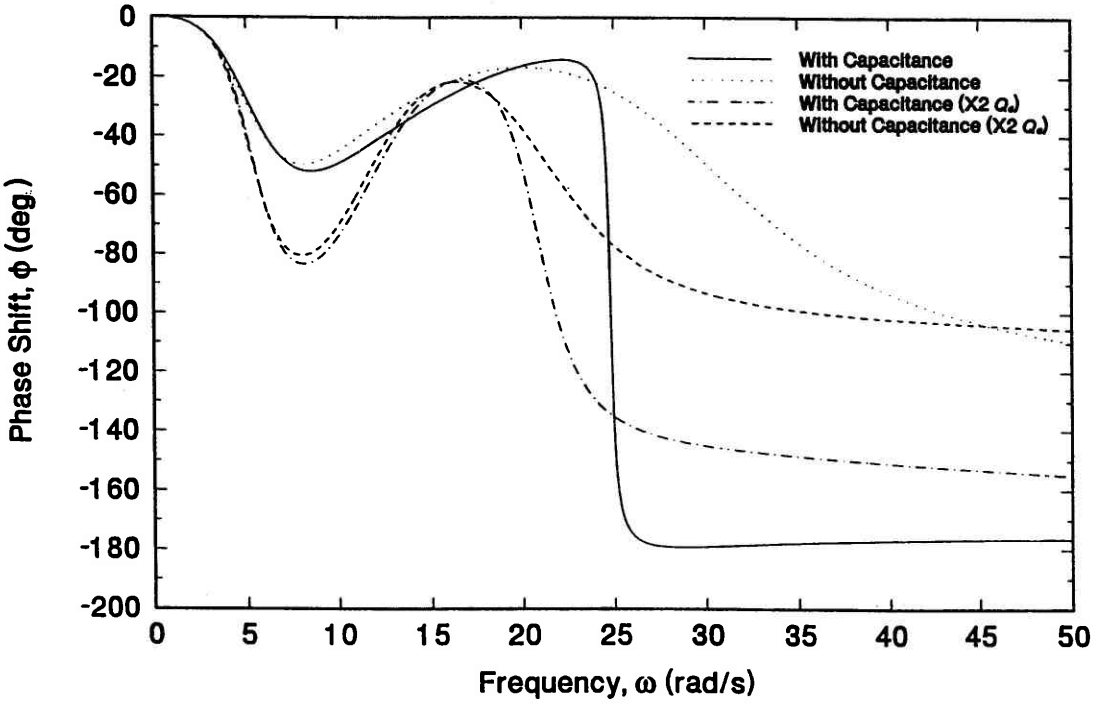


Figure 23 Effect of air compressibility on heave phase response for low and high flows

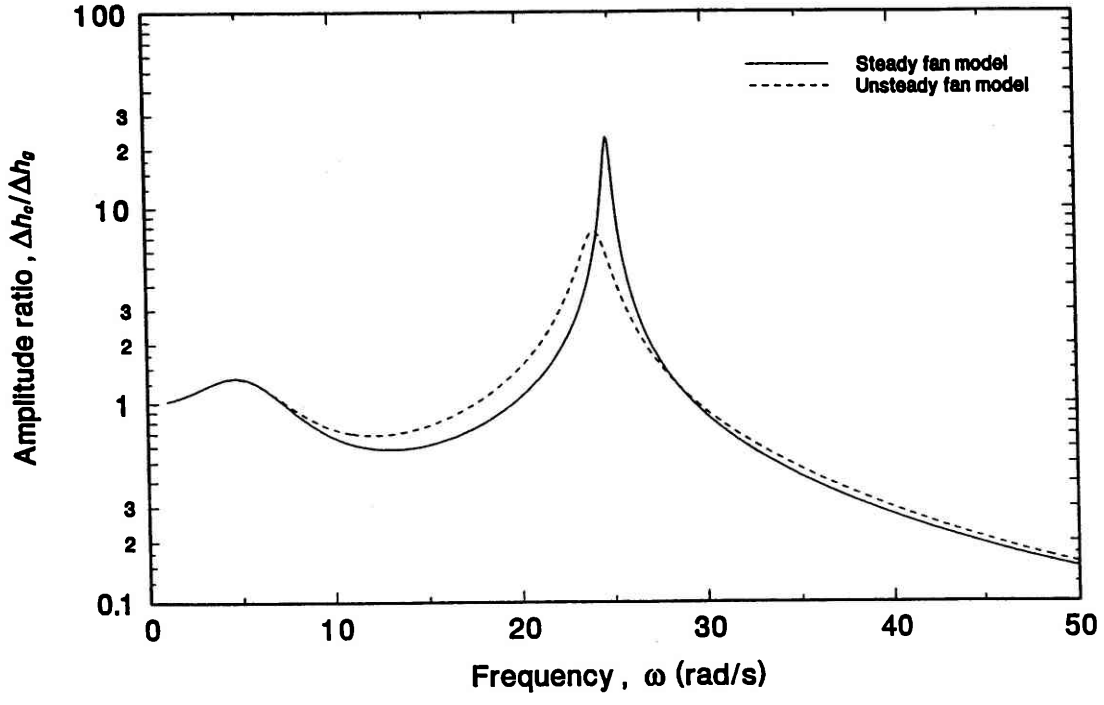


Figure 24 Dynamic fan effects on heave amplitude response

more prominent at the reduced cushion flow rates characteristic of modern designs. Finally, unsteady fan response can introduce major phase-shifts in the neighbourhood of the skirt mass resonance, and thus contribute to the onset of skirt bounce.

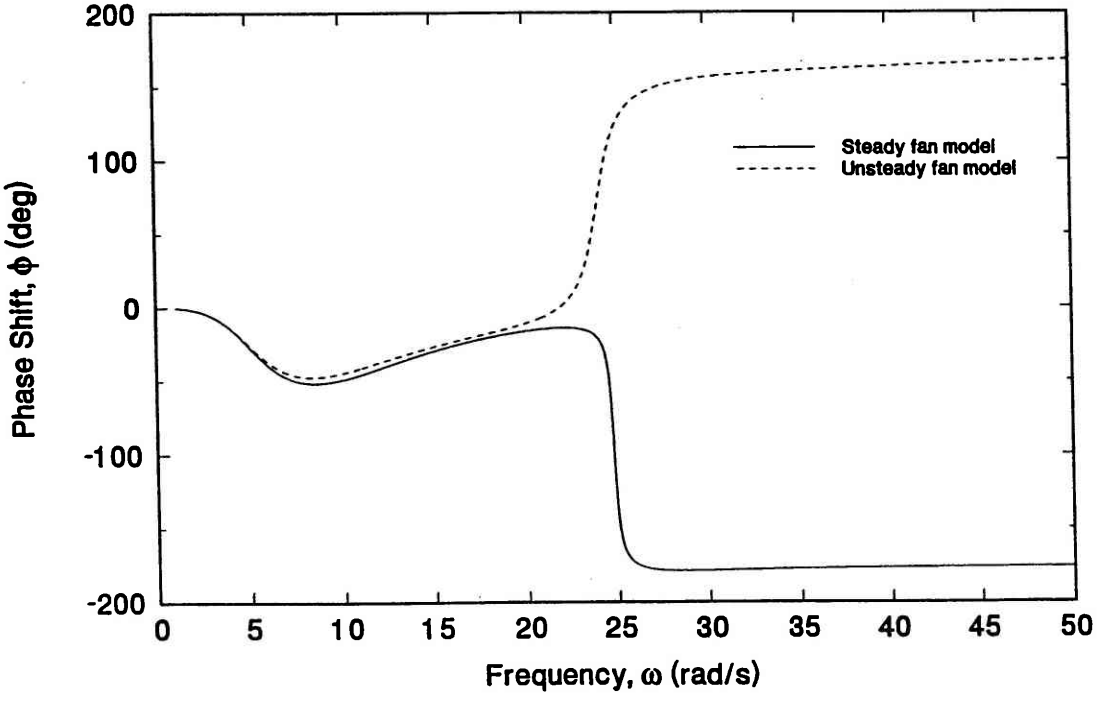


Figure 25 Dynamic fan effects on heave phase response

We remark that the present investigation omits many factors which may significantly modify the nonlinear phenomena described above. Considering only those appropriate to the two-dimensional configuration of Figure 2, three are noted here. The first and perhaps most obvious is the role of the anti-bounce web. Second, observations of the laboratory model show that, during skirt bounce, the outer bag's instantaneous shape is not a circular arc, but takes the form of a standing wave. This suggests that a distributed mass model may be required to adequately describe behaviour at frequencies in the neighbourhood of the skirt mass resonance. Third, as noted above, viscoelastic phenomena in skirt materials can introduce sources of damping which might significantly modify the results presented here.

Finally, we note that the present investigation suggests that, notwithstanding the highly nonlinear phenomena observed here, linear analysis can be used as a design tool.

ACKNOWLEDGEMENT

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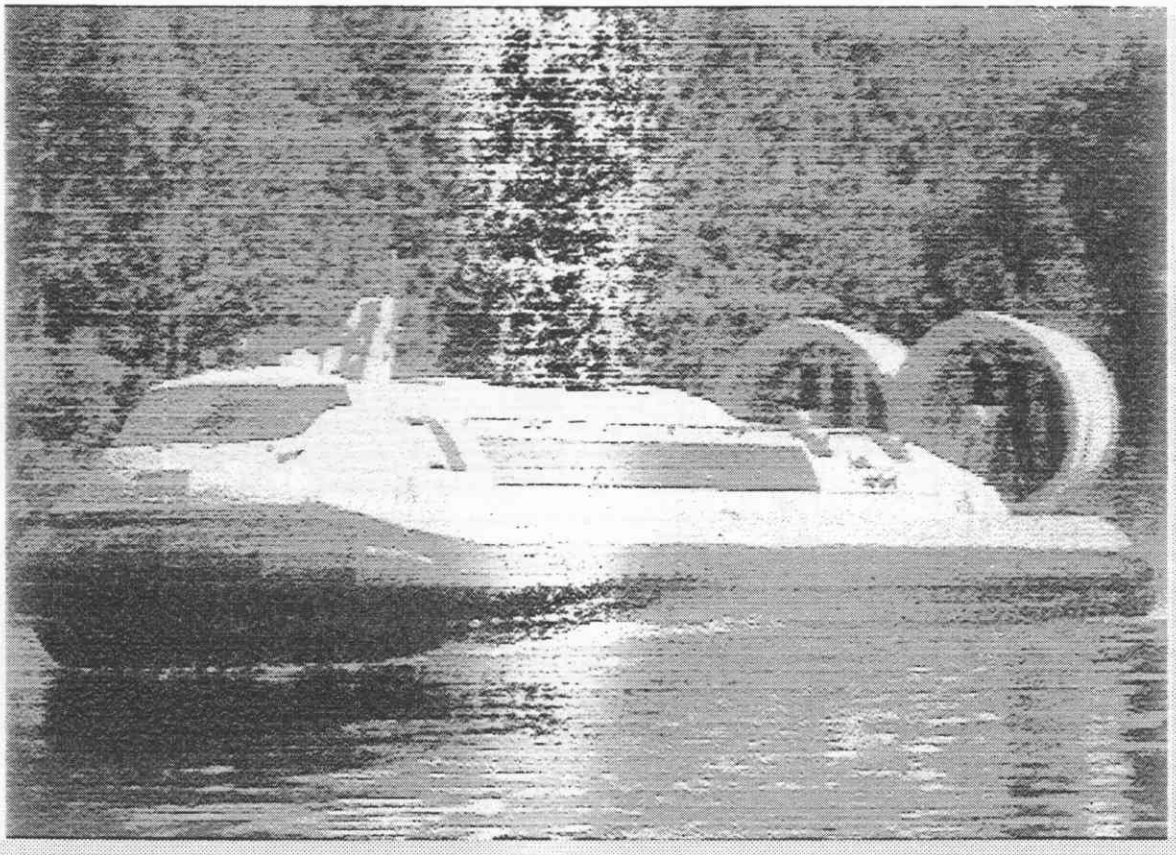
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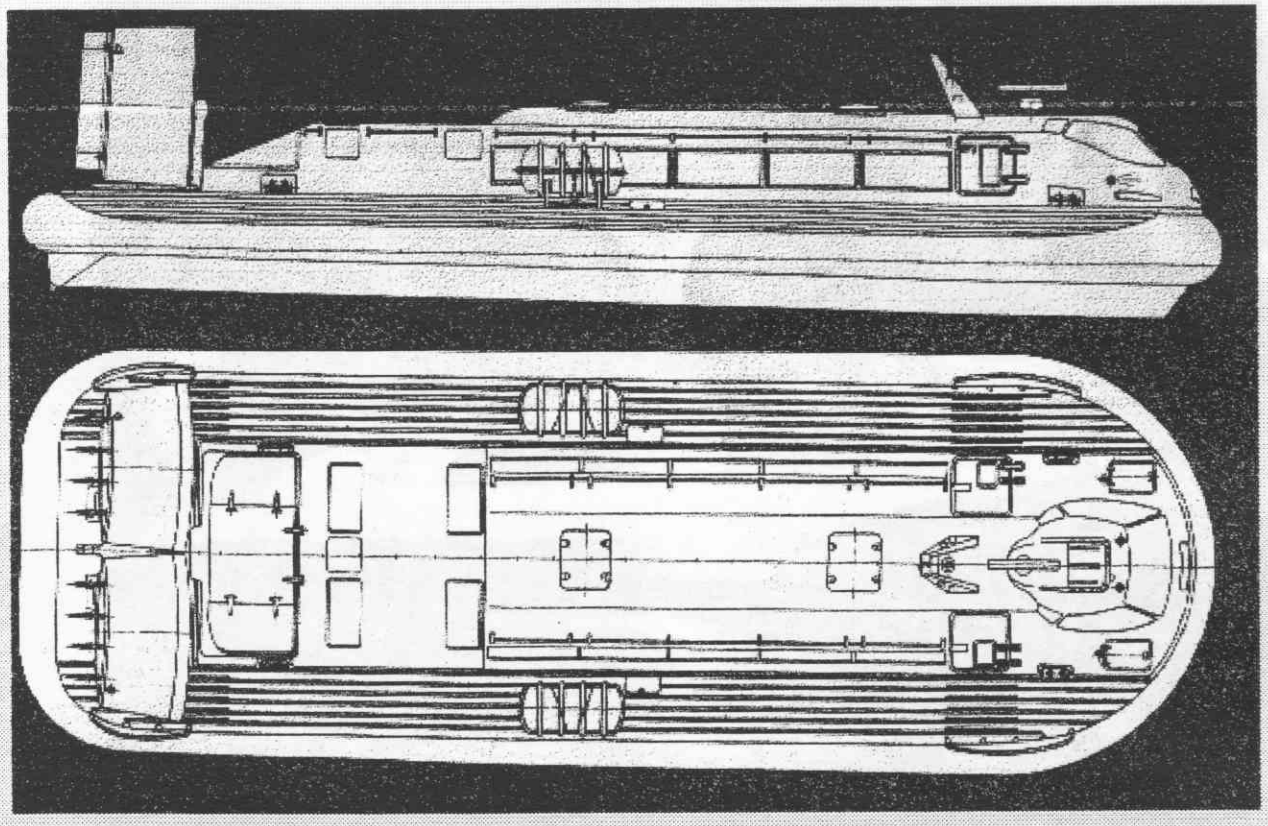
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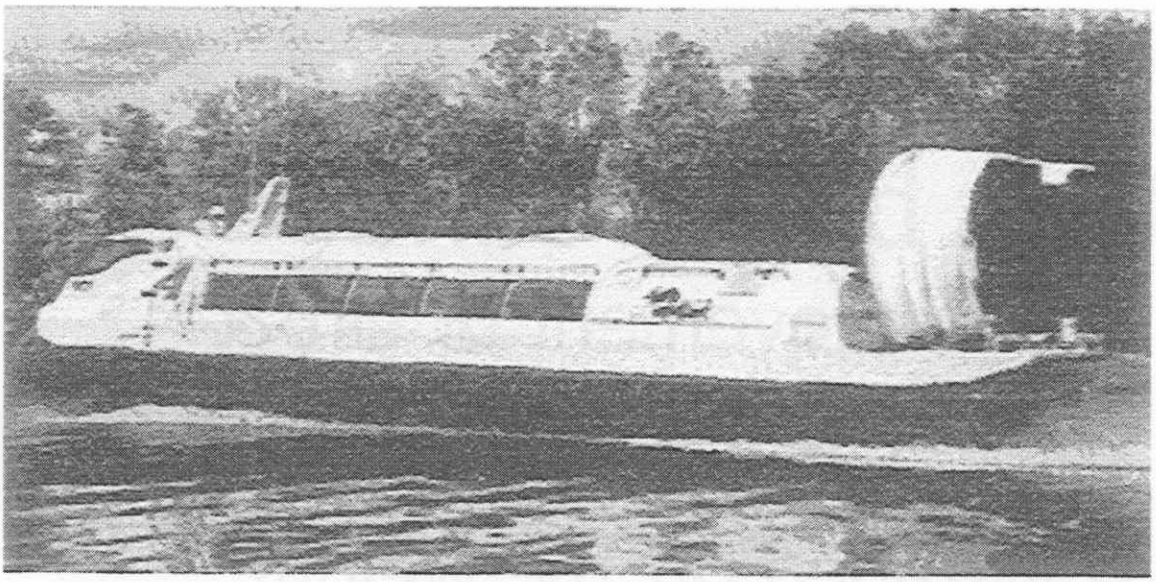
Retrofitting Irbis with the PW205/206 Gas Turbine



•Irbis

Introduction





Irbis

The case made here is a reversal of a trend based on the latest available information concerning small gas turbines, the baseline Irbis potential and a departure from orthodoxy, which is necessary to advance the use of Hovercraft as we move towards the millenium.

When the British improved the efficiency of Lift Systems and Skirts, they departed from the use of gas turbines as power plants, and instead began using air-cooled diesels, accepting the weight penalty as a trade off for the increased air cushion efficiency. The AP1/88 is proof of the effectiveness of this strategy.

However it was 15 years ago that AP1/88 serial #001 was launched and considerable advances have been made in the small gas turbine area. It is now time to revisit the use of small gas turbines in hovercraft and this paper examines a proposal to retrofit the Russian Irbis hovercraft with the PW205/206 series gas turbines.

Basic background

- U.K improvement of Lift & Skirt Systems in the 1980's.
- U.K traded off the weight penalty of using diesel power versus the efficiency increase in Cushion Systems.
- Over 15 years since this happened & now Gas Turbine advances call for review of these power plants for use in ACV.

The British made significant advances with their fully responsive bag and finger configurations in the 1980's to an extent where reported efficiency increases approached 30%. This gave them an opportunity to look at some of the other problems of Gas Turbine usage and maintenance, particularly with regard to operations in (at the time) Third World Markets. Gas Turbine Maintenance and Repair & Overhaul demanded significant skill levels, which were not always available in the locations in which hovercraft operated. There was also the problem of available fuel supplies for the Engines in out-of-the-way places. Most other transportation devices in the potential market areas used diesel power, so the British decided to absorb the weight penalty and install air-cooled diesel engines in place of the Gas Turbines in their new generation hovercraft, the AP1/88.

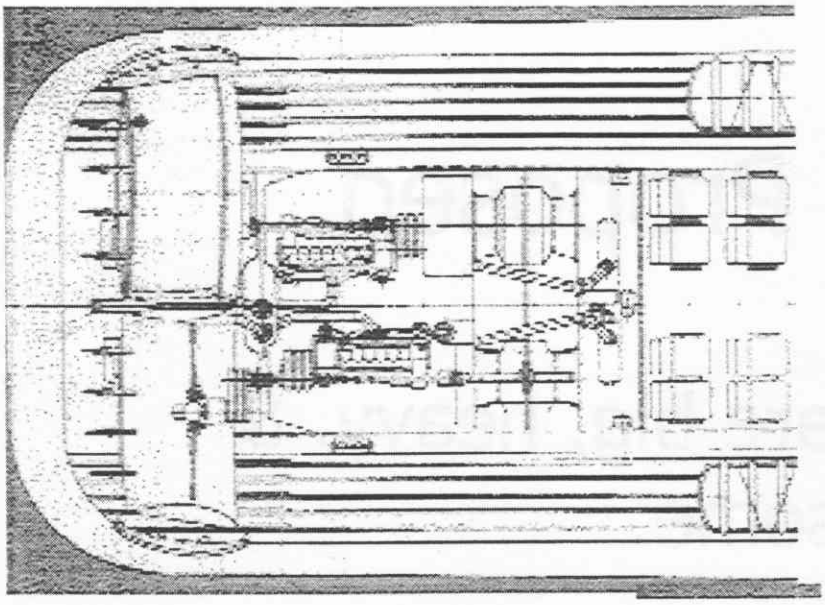
The AP 1/88 Trend Setter

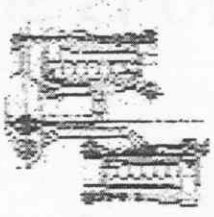


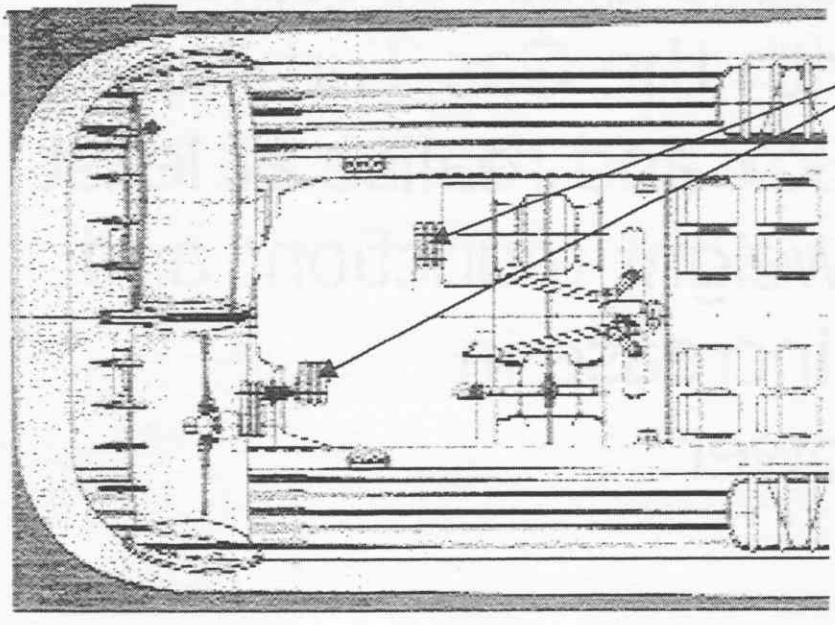
What is Proposed

- Diesels are big, heavy, & cumbersome.
- The PW205/206 is small, light & reliable.
- Remove the diesels, replace them with the Gas Turbine & a GearBox and realise at least 650kg weight reduction; and a 27% increase in horsepower.

The Irbis Engine Room

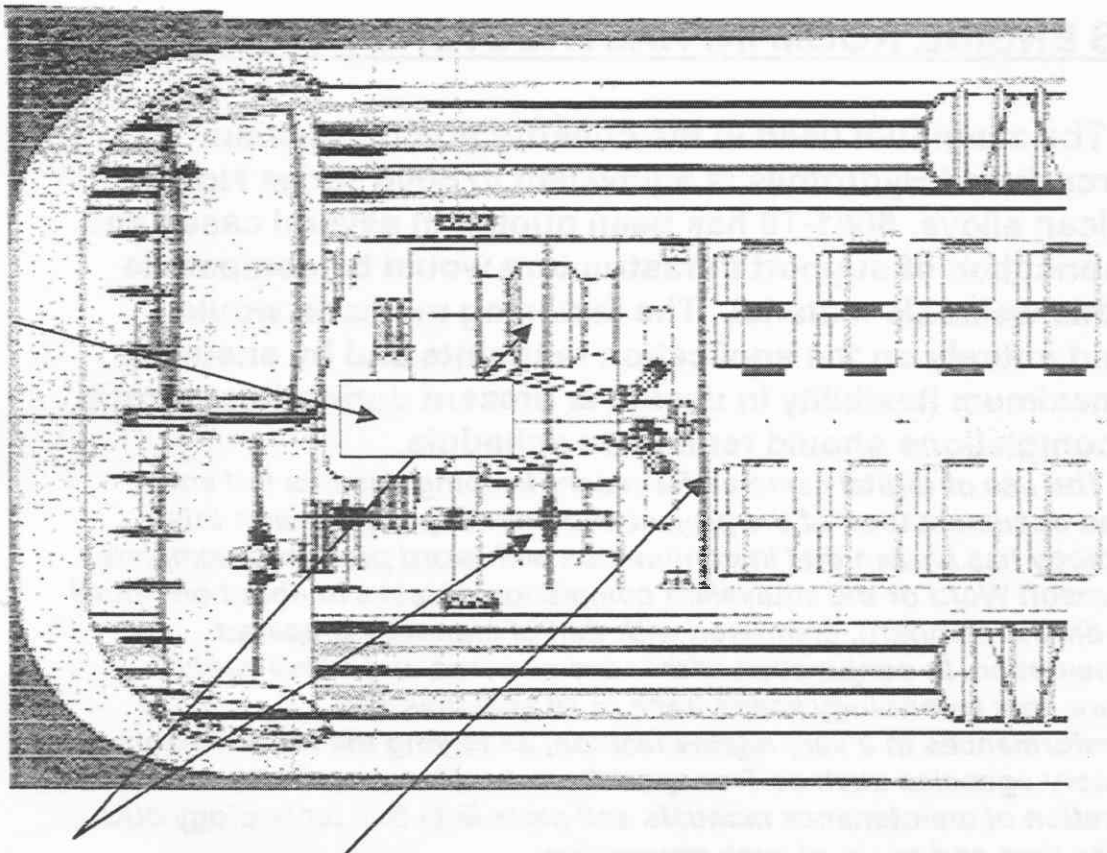






Both Diesels removed, but drive sheaves and belts left in situ

PW205 in this space.



Fans and bulkhead moved aft providing 4 extra seats. Enclosure design requires thought to prevent blanking of propellers

IRBIS ENGINE ROOM INFRASTRUCTURE NOTES.

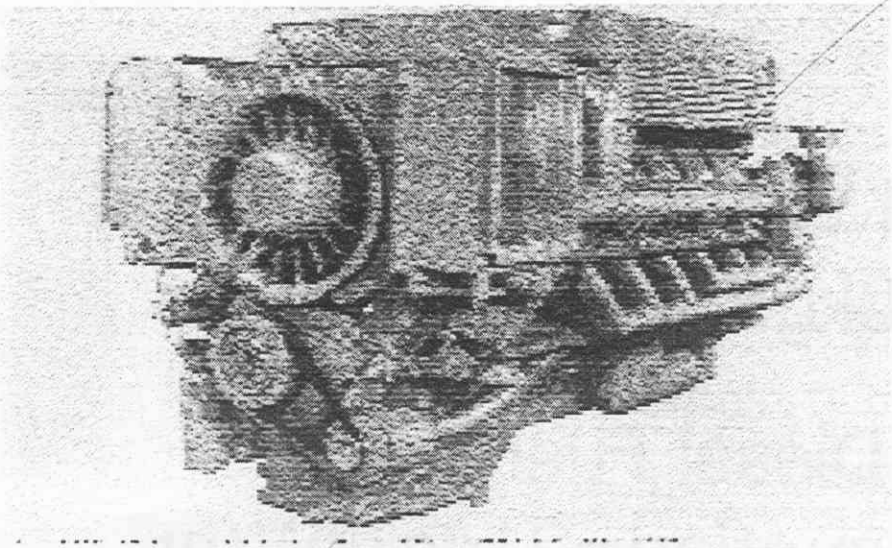
The aluminum used in the construction of Russian Hovercraft and Hydrofoils is equivalent to 6000 series North American alloys. 6061-T6 has been quoted in several cases and the fabrication of support infrastructure would be compatible with this weldable material. The fastening methods would depend entirely on the application restraints and by ensuring that maximum flexibility in design is present during this retrofit, task completions should remain on schedule.

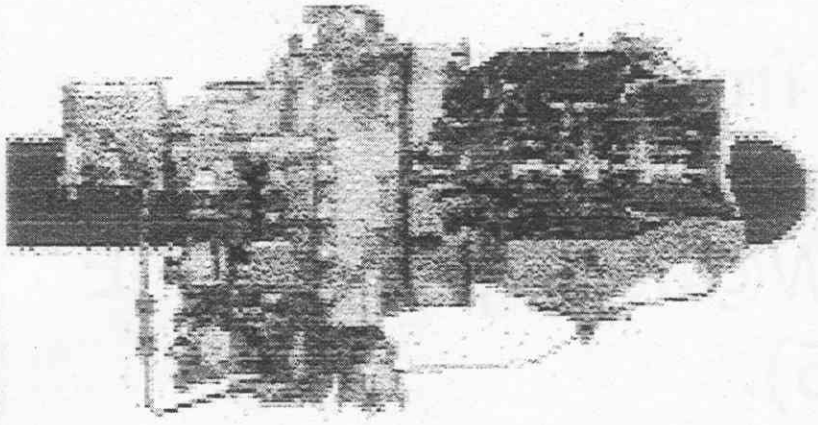
The use of digital cameras for record keeping ensures full and detailed documentation of the project and prior experience with this technology has shown that in conjunction with word processor templates in Microsoft Word or the equivalent completion of tasks in about one-third of the time is standard, compared with that of manually prepared documentation. In conjunction with video cameras and frame capture software, this technology keeps track of all activities and nonconformances in a very legible fashion, satisfying the requirements of regulatory agencies such as Transport Canada. Moreover in the preparation of maintenance manuals and parts lists this technology cuts both the time and costs of such preparation.

Air Management for the PW205 is in process, but requires to be fine tuned once the diesels have been removed from the Engine Room. With the volume freed up by that removal, carefully designed labyrinths would remove most of the particles detrimental to the PW205 operation, and by thoughtful design, any restrictions in the passageways affecting PW205 performance may be opened up during over water operations since particle hazards are reduced in these circumstances. Spray conditions would be controlled by skirt flaps and deflectors, once spray patterns have been determined and video taped.

With the installation of the PW205, vibration levels will be reduced considerably, and it should be possible to remove some of the sound deadening materials installed for diesel use. Where noise attenuation is required, there are a number of proposals being considered at this time and an update will detail these.

This shows the Diesel and the PW205



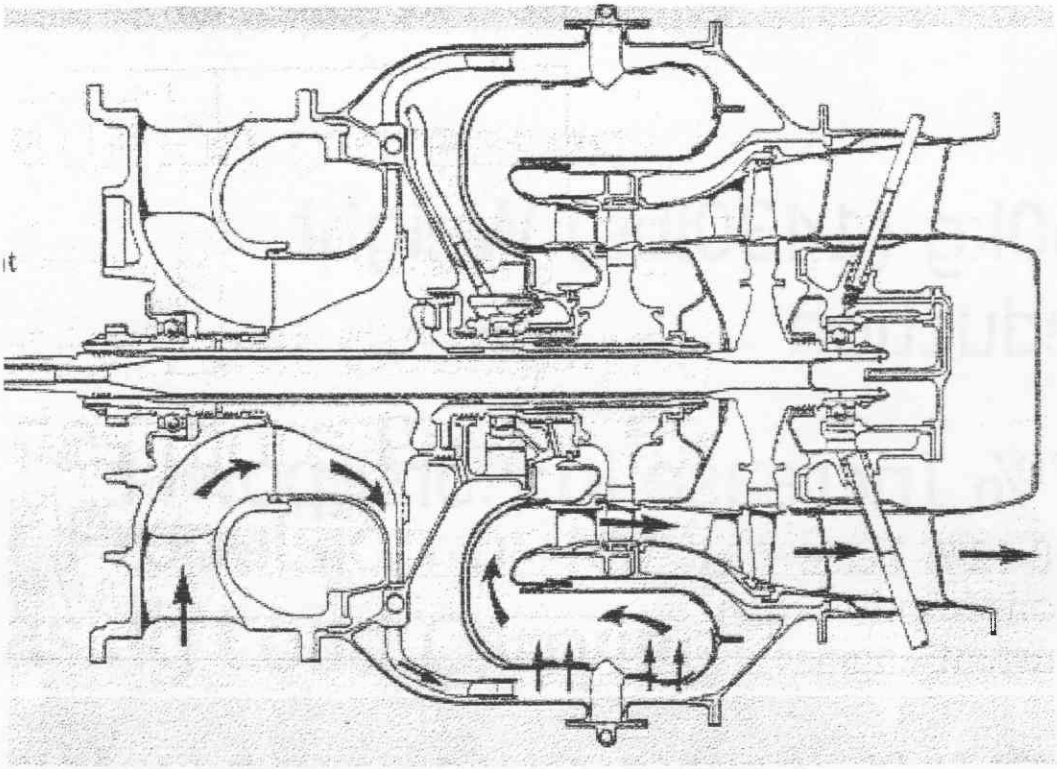


Comparison of the Power Plants

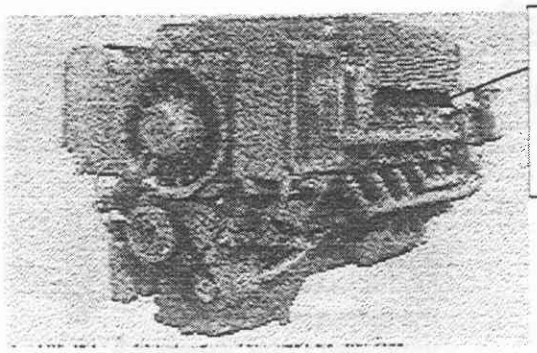
- Diesel Weight=1020kg Total vs 370kg for PW205.
- Total Diesel Fuel Consumption=214g/kW/hr (341g/kW/hr for PW205).
- Power from TWO diesels=282kW@2500rpm. (358kW@6000rpm for ONE PW205).

The PW205/206

- 650kg (1430lbs) Weight Reduction
- 27% Increase in Horsepower

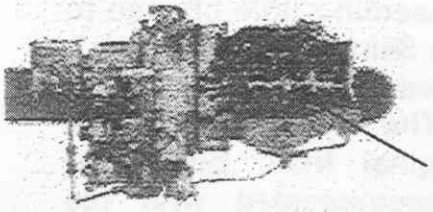


PW205 CROSS SECTION



This is the diesel in Irbis 510kg (1122 lbs); SFC=214g/kWh; 141kW@2500rpm

2 diesels 1020kg (2244 lbs) 282kW@2500rpm



This is the single PW205/6 Gas Turbine replacing two of the above diesels
259kg (570lbs)
+111kg(244lbs g/box)
370kg (814lbs)
SFC=341g/kW/h
358kW@6000rpm

650kg (1430lbs reduction in weight)
27% increase in power output

A pilot project incorporating the proposed rework to the Irbis is attractive since the increase in power can be traded off by increasing the standard payload and/or increasing the cruising speed and the maximum speed.

IRBIS STATISTICS AND NOTES

IRBIS "AS-IS" (Extrapolated)	IRBIS "AS-PROPOSED " OPTION #1	EFFECT
AUW=23583 lbs	**25500**	**Increased Revenues**
HP=378	**480**	**Increased Performance**
lbs/HP = 62	**53**	**Higher Cruise & Top Speed**
Cushion Area = 480(Approx)	480	No Change
Cushion Press = 50 psf	**53**	**6% Increase**
Fan Delivery Press = 65 psf	**68**	**6% Increase**
Engines as % of AUW = 19%	**3.2%**	**Improved Polar Moment & Manoeuvrability**

There are other options to the retrofit.

The above is the most straightforward representing little change to the basic layout of the Irbis and maintaining the Skirt Geometry "as-is". The most dramatic change will be in the craft responsiveness because of the much reduced Polar Moment of Inertia. The Russian design has probably compensated for this in the original Irbis, but any compromises made, do not have to be accomodated with the proposed retrofit.

The initial proposal would put a majority of the power increase to Propulsion to give a higher cruising speed and top speed. The slight fan delivery pressure increase can be accomodated within the present configuration of blowers and ducting, and the power delivery from the PW205 would be controlled via FADEC.

In the Planning Stages (as this goes to press), there are three scenarios.

1..... Where the Irbis for sale in Olcott New York State (just outside Buffalo) would be ferried across Lake Erie to an outfitting shop in Port Colborne, Ontario, (at the Lake Erie end of the Welland Canal) and there, in collaboration with Pratt & Whitney Canada, the retrofitting operations would be carried out.

2..... Where an Irbis would be bought from the Neptun BoatWorks, and retrofitted with the PW205 at a location to be determined, depending on the choice of the partners involved.

3..... Where the Neptun Boatworks, Pratt & Whitney and A.N.Others would launch a joint venture and partnerships to retrofit or build from scratch an Irbis designed around the use of the PW205.

Item 1 is favoured, since the costs are predicted to be the lowest for any of the scenarios.

The modern Diesel is at the end of its evolutionary cycle. Very few significant improvements are going to happen over the next 7 years.

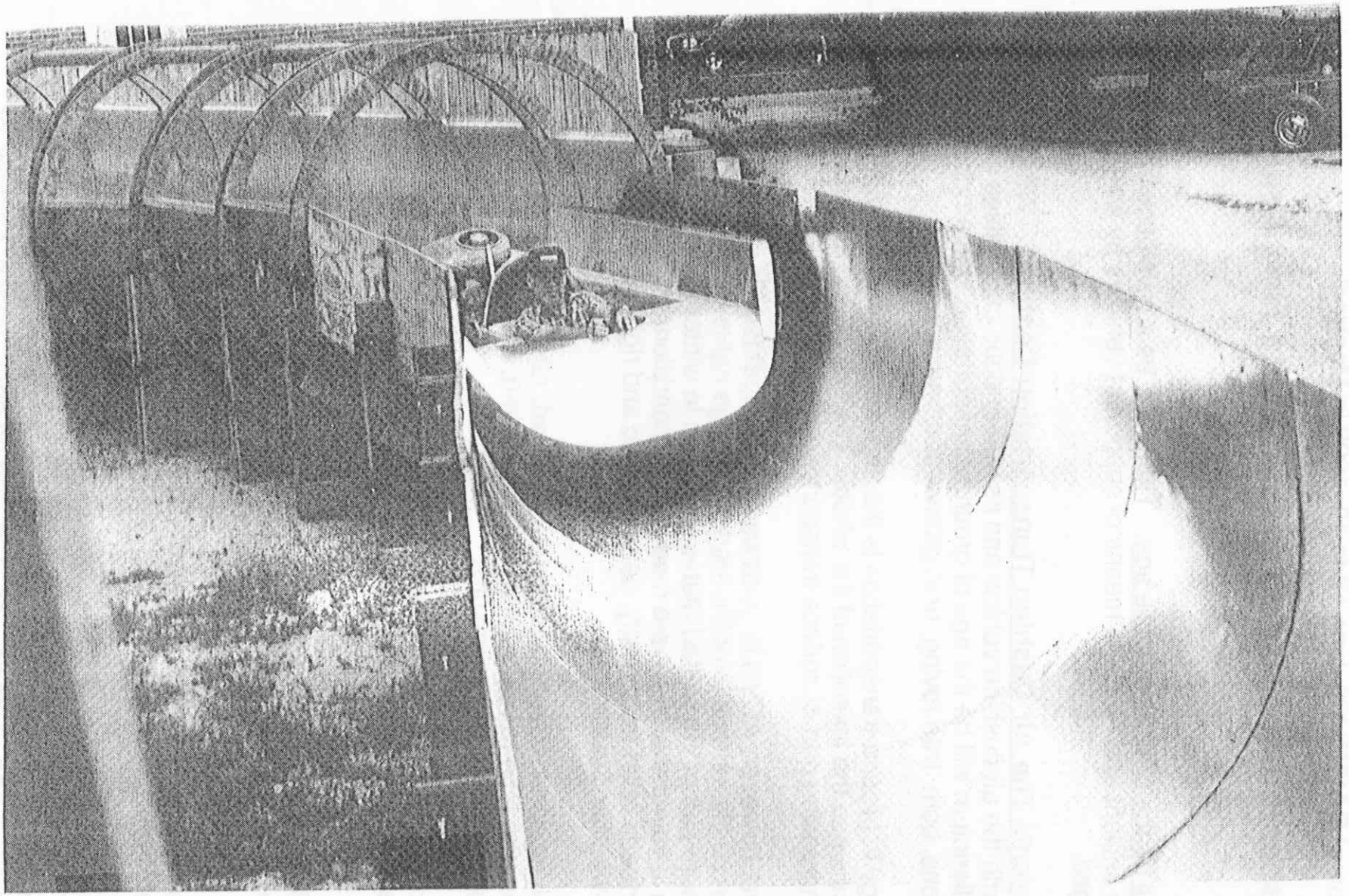
In contrast significant advances in CFD will lead to more efficient internal flow systems and fuel injection improvements and Materials Technology advanced materials will see further increases in thermal efficiency, where Gas Turbines are concerned.

The approximately 100 year reign of the Reciprocating Power Plant has been long, evolutionary, and fruitful.

Rotary Power Plants have set out on a similar journey ... they will take much less time to evolve when utilised in applications such as portrayed here.

In Conclusion

- Substitution increases Revenue generating Payload, and provides more Power for either Propulsion or for increasing Load Carrying capacity
- Both the Hovercraft & Power Plant Manufacturers will profit by carrying out this modification since the Irbis will perform better and earn larger revenues.



A Ground Transportation System for the Twenty First Century.

For Presentation at **CACTS '98**, Montreal, Quebec, June 16 to 19, 1998,
Canadian Air Cushion Technology Society, Section of
The Canadian Aeronautics and Space institute.

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Paper for Presentation at **CACTS '98** June 16 to 19, 1998 in Montreal.
William R. Bertelsen, M.D., V.P. R&D, **Aeromobile Inc.**

A Ground Transportation System for the Twenty First Century.

I. Introduction:

The Century 2000 will be the post automobile age. There will be a revolution in ground transportation. The ancient and obsolete means of support of vehicles by wheels on roads will be challenged.

Century 2000 will become **The Air Cushion Transportation Century**. While only those of us familiar with the air cushion vehicle and its tremendous capabilities now realize it, the new millennium will be the age of ground transportation with amphibious vehicles on air cushions, both free roving, or in groove or tube guideways.

Air cushion technology in ground transportation is the first major paradigm shift in surface travel practice since the invention of the wheel. The free roving amphibian ACV's are to be an increasing part of surface transportation in Century 2000.

The newest derivative, however, ACV's in guideways, can supersede inefficient, unguidable wheels on costly, unmaintainable road and bridge rights-of-way. While mainly only the Northern half of the United States is subject to winter snow, sleet, ice, etc., most of Canada is vulnerable to severe road surface conditions in winter. Every country in the world needs relief from costly, deadly, traffic and rights-of-way problems, by an automated, all-weather System.

Though not yet widely understood, nor adequately exploited, air cushion supported vehicles in guideways, can lead to vast savings of money, time, lives, and possibly, saving the earth, its atmosphere, and humanity.

II. Aeromobile Inc. Objectives and Progress in the Evolution of, and the Derivatives of, the Air Cushion Phenomenon in Four Decades of Research and Development.

A. Aeromobile Inc. Objective Number One: To Overcome the Control and Steering Problems of the Amphibious Air Cushion Vehicles for the 21st. Century.

Aeromobile Inc. has resolved this problem with **The Gimbal Fan System of integrated lift, Propulsion, and Control of Air Cushion Vehicles**.

In order to make the amphibious ACV's responsive to driver commands, **Aeromobile Inc.** has developed **The Gimbal Fan System**. (See Figs. 1., 2., 3., 5, 6, and 7.) **The Gimbal Fans** can totally control amphibian ACV's, positively and forcefully overcoming winds, grades, and obstacles, on land, and on open, frozen, shallow, or

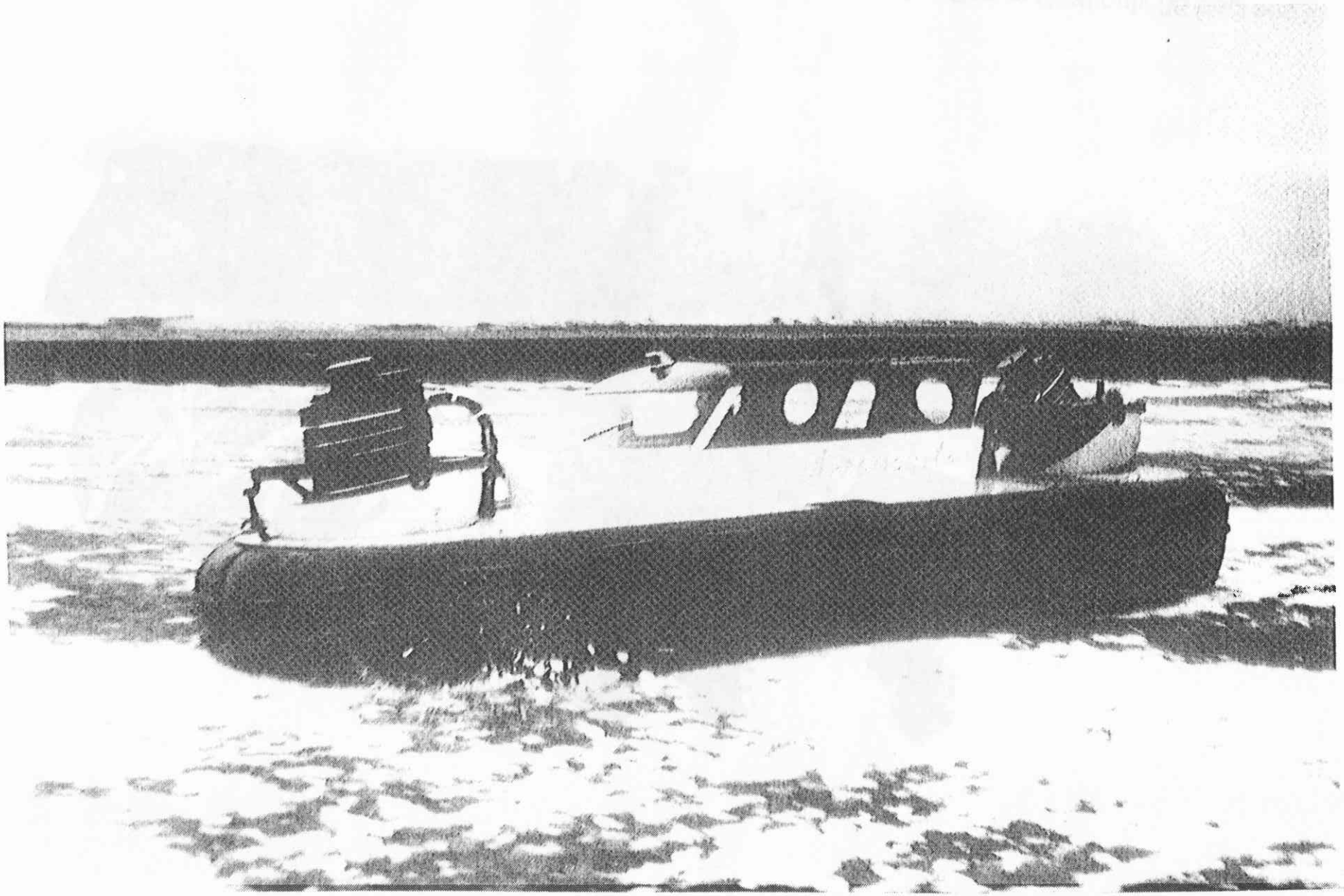


Figure 1. **Twin Gimbal Fan Aeromobile 13** at cruise speed, as shown, it is thrusted and steered only by stern **Gimbal Fan**. While both **Gimbal Fans** supply lift, thrust, and steering, the bow **Gimbal Fan**, as shown, is contributing lift air only.



Figure 2. **Aeromobile 14** on snow with three passengers. the single **Gimbal Fan** is tilted only 35 degrees to produce adequate thrust for high speed travel and with sufficient lift air to pressurize the base.



Figure 3. **Aeromobile 14** on water, It is at "hump" speed. Lift, thrust, and steering, braking, and backing, are all achieved by the single **Gimbal Fan**.

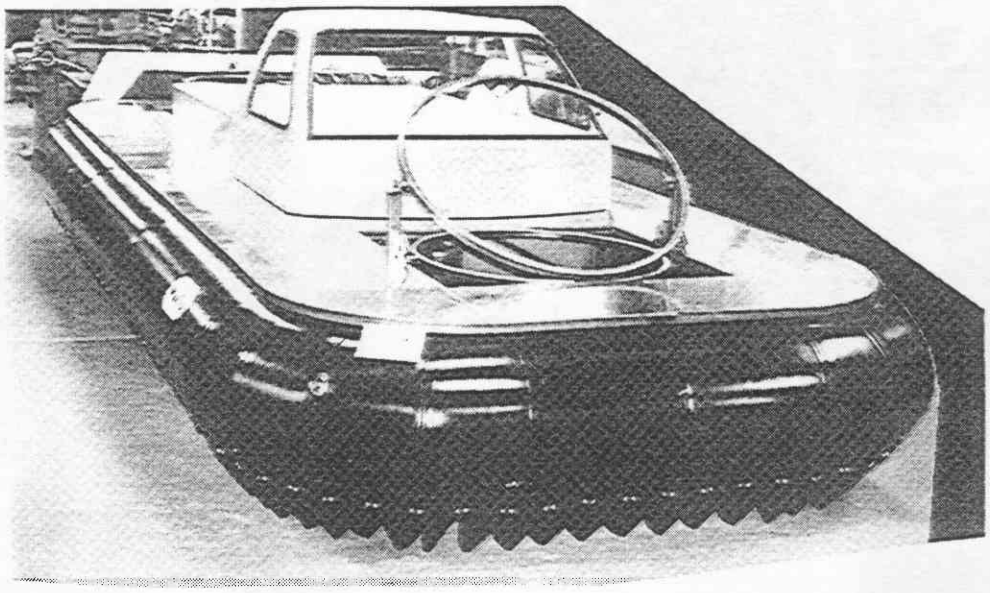


Figure 4. **The Aeromobile 2000** at it's state of construction in March 1998. The **Gimbal** rings are in place, steel **Gimbal** ring mounts, the **Hirth** engines, hydraulic controls and instrumentation are yet to be installed in them. The **Wing inflatables** flotation surrounds the craft, with the air cushion skirt segments fitted below.

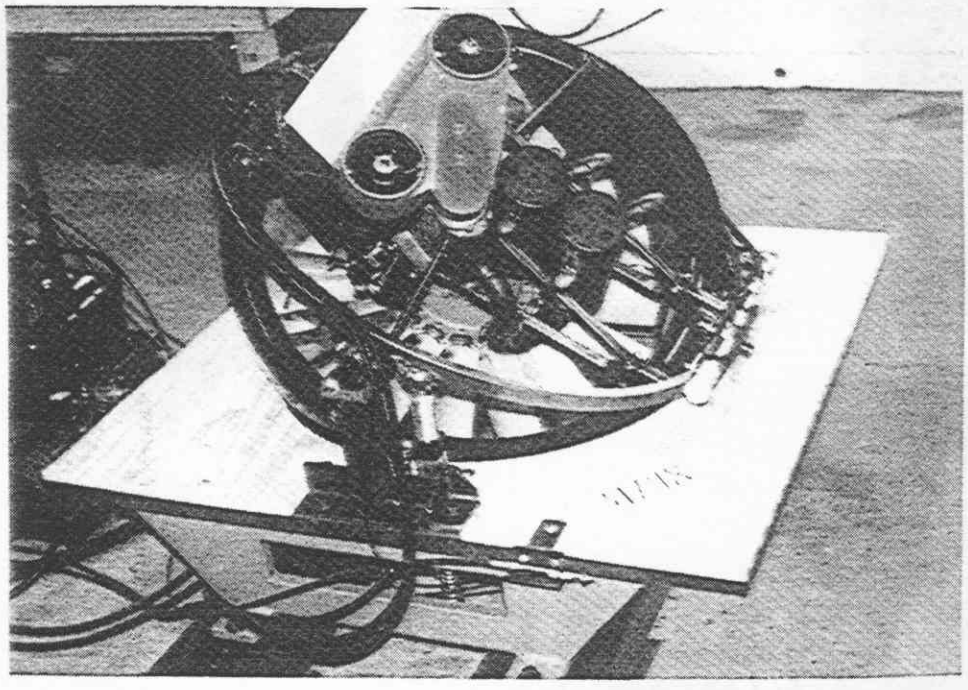


Figure 5. The 120 h.p. **Hirth** engine powered **Aeromobile 2000 Gimbal Fan** is shown installed on the test stand . It is mounted on a steel ring with two axis bearings to allow it to be remotely hydraulically tilted it fore, aft, and laterally for directing it's thrust in all 360 degrees. The fore, aft and lateral tilt hydraulic cylinders are visible on the edge of the **Gimbal** ring, both hard over actuated.



Figure 6. The 120 h.p. **Hirth** engine powered **Aeromobile 2000 Gimbal Fan** is shown at zero fore-aft tilt, and hard over lateral tilt. Again the hydraulic cylinders can be seen at the edge of the unit.

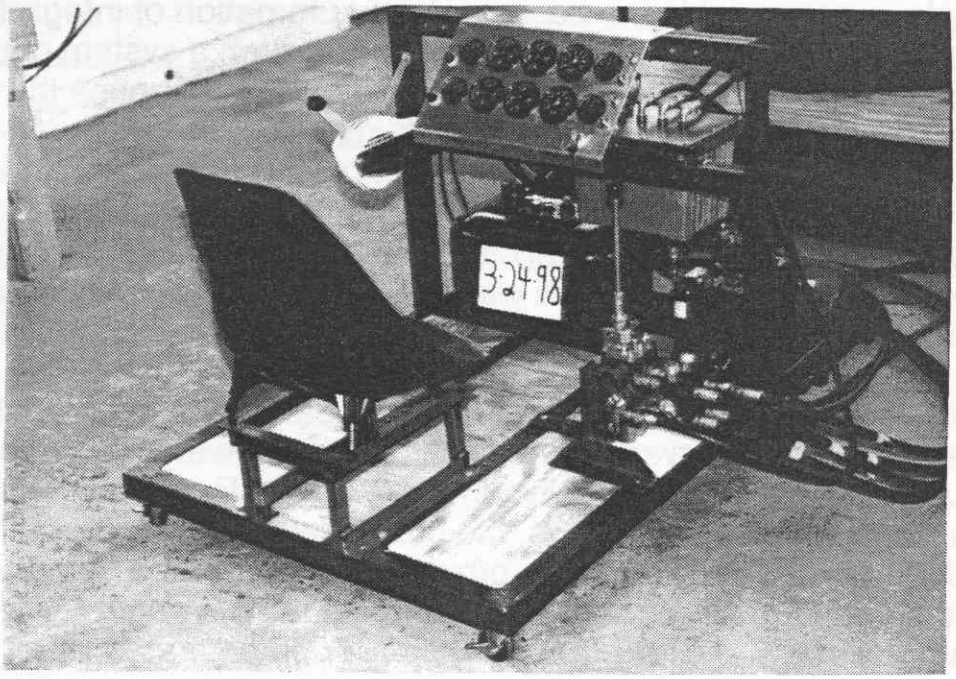


Figure 7. View of the **Aeromobile 2000 Gimbal Fan** control station showing the bow and stern **Gimbal Fan** instruments, throttles, switches, and the bow **Gimbal Fan** "Joy stick" for directing of the powerful thrust in all 360 degrees, proportionately, incrementally, or "hard over", instantly cancelable and reversible.

rushing water. The amphibian **Twin Gimbal Fan Aeromobile** can move sideways and diagonally as well as forward and backward. It can pivot in place. It has high-speed braking capability with full steering. In short, only **The Gimbal Fan System** has the demonstrated potential to adequately control an air cushion vehicle under all conditions.

On the basis of amphibious capability and performance, there should be more air cushion vehicles than power boats. ACV's allow year round water travel for all missions, all surfaces, all seasons, all weather, and in all climates. Much of off-road transportation and hauling can be done with various sizes of amphibious **Multiple Gimbal Fan Aeromobiles**. ACV's go where wheels fear to tread. Personal and public amphibious **Aeromobiles** and air cushion ferrys for mass transit or freight can be used on much of the land, and in all the three quarters of the planet covered by water. Century 2000 will be **The Air Cushion Transportation Century**, on or off automated guideways.

B. Aeromobile Inc. Objective Number Two: The Aeromobile-Aeroduct System of Automated Transportation.

In addition to mass producing the amphibian **Twin Gimbal Fan Aeromobile 2000**, and its successors, the objective of **Aeromobile Inc.** is to establish the wide acceptance and deployment of special air cushion vehicles (ACV's) called **Aeromobiles** in special tube or groove rights-of-ways, called **Aeroducts**.

Such a System alone can provide the basis for total automation of integrated personal and public transportation. We will attempt to prove that such a system could be built and superimposed over existing streets and roads at far less expense than even repairing roads and bridges up to minimum standards. With its inauguration would come a vast rejuvenated landscape, the elimination of all parking lots, and all land devastating interchanges, returning the land to its natural and beautiful state. In addition to realization of significant ecological benefits, there will be savings in time, money, and lives. The proposed System will make transportation accessible not only to licensed drivers, but to people of all ages, disabilities, and economic status.

Note: The fact that no rights-of-way exist for any new transportation modality is irrelevant. When Columbus arrived on the continent, there were no horse trails, no roads, mud or paved, no rail roads, no Lincoln Highway, no Route 66, no Interstates. When each new advance met their needs, the public demanded and got their new right-of-way. All that is needed is that the proven **A-A System** be demanded by the public. Perhaps automated air cushion vehicles in guideways seem too good to be true, but are nevertheless absolutely true as we have demonstrated in full scale.

In the last three decades **Aeromobile Inc.** has modified the amphibious air cushion vehicle airframe and skirt to conform to, and operate in, a guideway to create this new guided transportation modality. We built a full scale, one passenger demonstration

Aeromobile 17 to fly in a cylindrical groove right-of-way on our plant property. (See Figures 8, 9, 10, 11, 12, 13, 14., and 15.) It is a successful proof-of-concept prototype, absolutely guided, and therefore can be automated, and is, like all ACV's, all-weather amphibious. It has been an in-house R&D funded project, by this small Company, evolved and improved over several years.

The demonstrator **Aeromobile 17** (The seventeenth in the Bertelsen series of man-carrying ACV'S built since 1958.), consists of an eleven-foot-long chassis for one passenger, the driver. It is powered by a 55 H.P. JLO engine set in a 36" diameter **Gimbal Fan** which pivots fore and aft only. With the **Gimbal Fan** running and positioned with its fan shaft vertical, all of the slipstream goes only into the lift chamber. The **Aeromobile 17** rises on cushion with one or two inches of clearance from the sheet metal groove, and remains hovering at rest. (See Figure 10.) Gravity keeps it centered in the groove. To travel forward, the driver tilts the **Gimbal Fan** to produce a powerful jet of air over the deck for forward thrust. The frictionless craft responds at once and moves at once with a slight tilt of the **Gimbal Fan**. For braking or backing up, he tilts the **Gimbal Fan** the opposite way. At speed on curves the **Aeromobile** centrifugates laterally, banking on the sides of the groove. (See cover photo, and Figure 15.) Unlike wheels on roads, the acceleration and braking by air thrust are always constant irrespective of surface conditions, sleet, water, snow, etc. This System can be totally automated, therefore, and in all-weather to stop precisely at a station like the vertical elevator.

The demonstrator **Aeroduct** ROW is a made up of semicircular open groove sections for simplicity and maximum visibility. The units are made up of 5-foot-long sections of plywood ends supporting 76" diameter 26 gauge (1/32nd. inch) sheet-metal grooves. In the straightaways, sections are bolted face to face and have smooth interconnecting surfaces. (See Figures 11., 12., 13., 14, 15, and VCR tapes). For the curves, the units were set at angles and the wedge-shape gaps filled with air-tight, smooth sheet metal. The curves of the prototype ROW are made up of a series of short flat segments, to which the flexible skirt conforms with little air loss.

This is a full scale, proof-of-concept prototype **The Gimbal Fan Aeromobile 17** flying in an **Aeroduct** groove ROW is incontrovertible evidence of the frictionlessness and perfect guidance of an ACV configured to the cylindrical groove. As all knowledgeable ACV people know, there is no limit to the mass which can be carried on air cushions. The demonstration vehicle and its guideway can be scaled up to carry any load of any size. It will do so totally automated, amphibiously, frictionlessly, in any weather, at high speed, as far as the ROW is extended, with perfect guidance.

The Initial introduction of **The A-A System** can be like that of the vertical automatic elevator, but going horizontally. Low cost **Aeroducts** can be installed elevated between well traveled points such as parking lots to airport gates, malls, office buildings, in and around amusement parks. Air cushion horizontal elevators can be built on industrial complexes, university campuses, shopping malls, etc. There is no

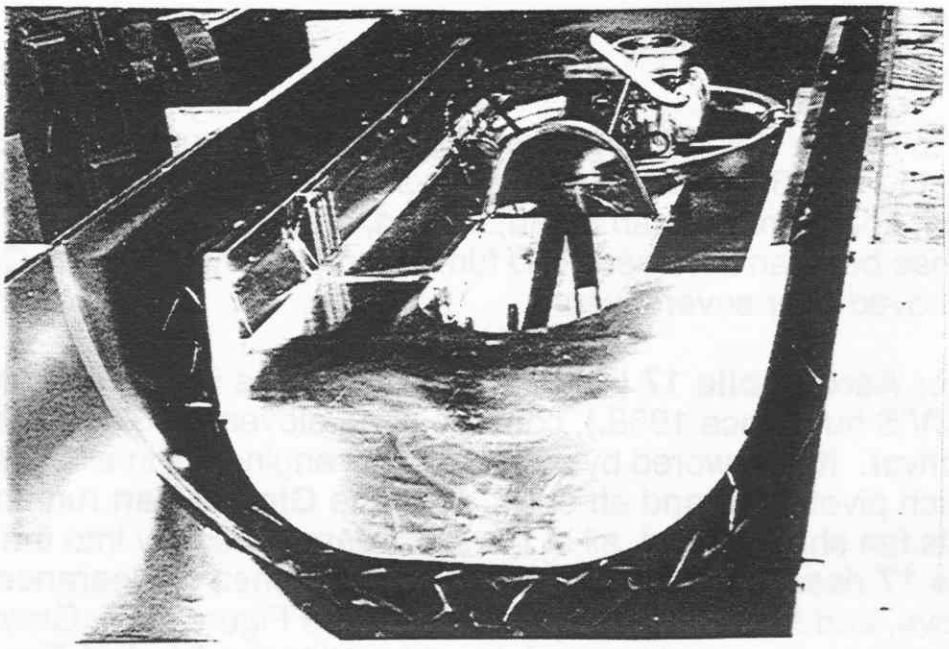


Figure 8. Left front view of the single passenger 800 lb. gross weight **Aeromobile 17** shown power off in its' sheet metal and plywood guideway.

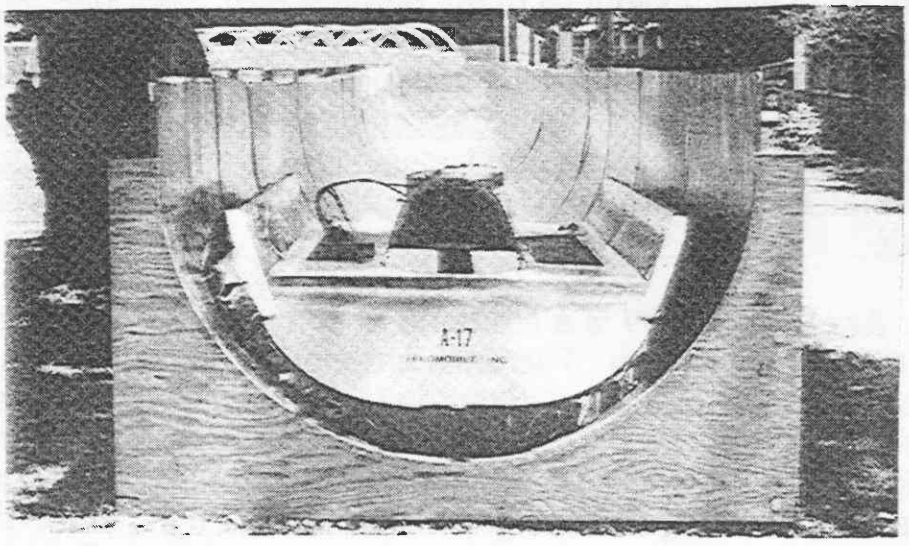


Figure 9. The **Aeromobile 17** at rest, power off, 8" skirt collapsed at the end of the 250 foot long groove ROW.

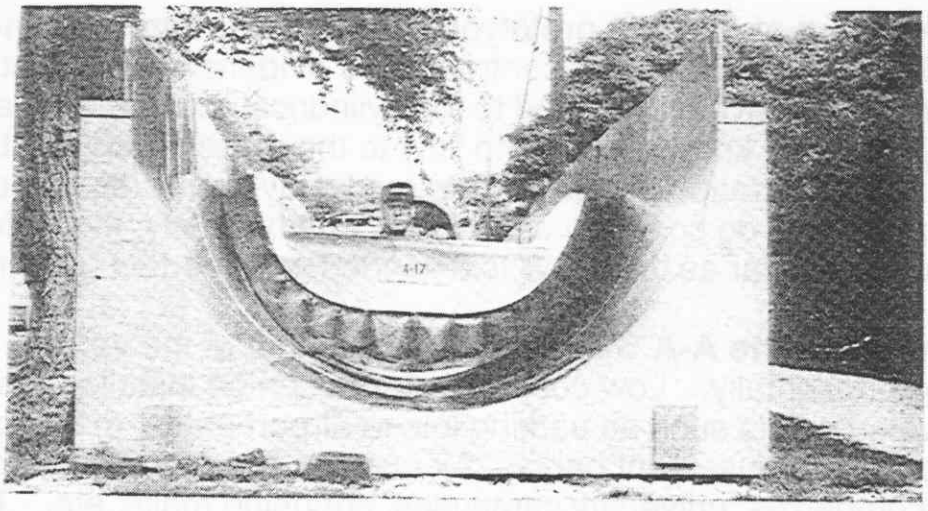


Figure 10. The **Aeromobile 17** on cushion at the end of the ROW with 1 or 2 inches of free air space between the skirt tips and the sheet metal guideway rendering it totally frictionless and perfectly centered and positively confined to the groove ROW.

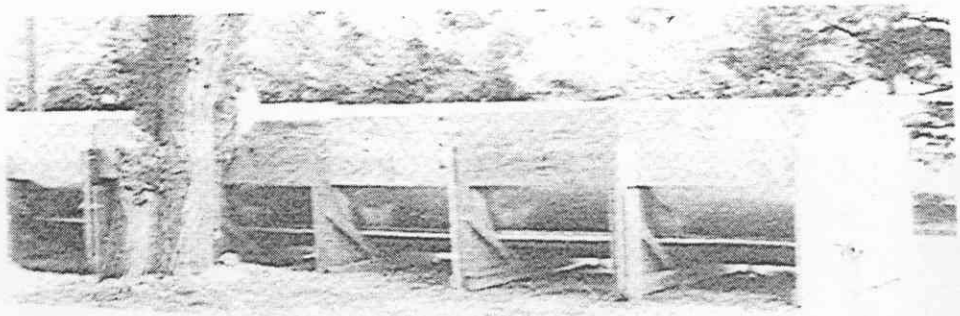


Figure 11. Side view of the end of the 76" diameter cylindrical sheet metal and wood proof-of-concept **Aeroduct**.

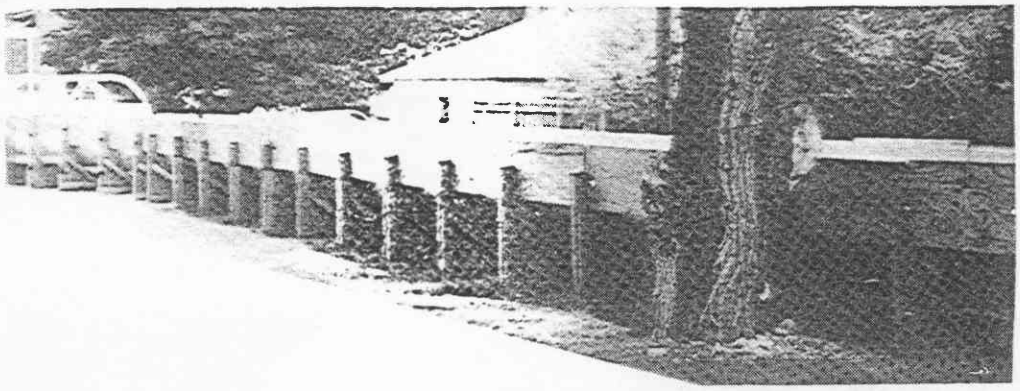


Figure 12. Oblique view of the West straightaway of the **Aeroduct** ROW.

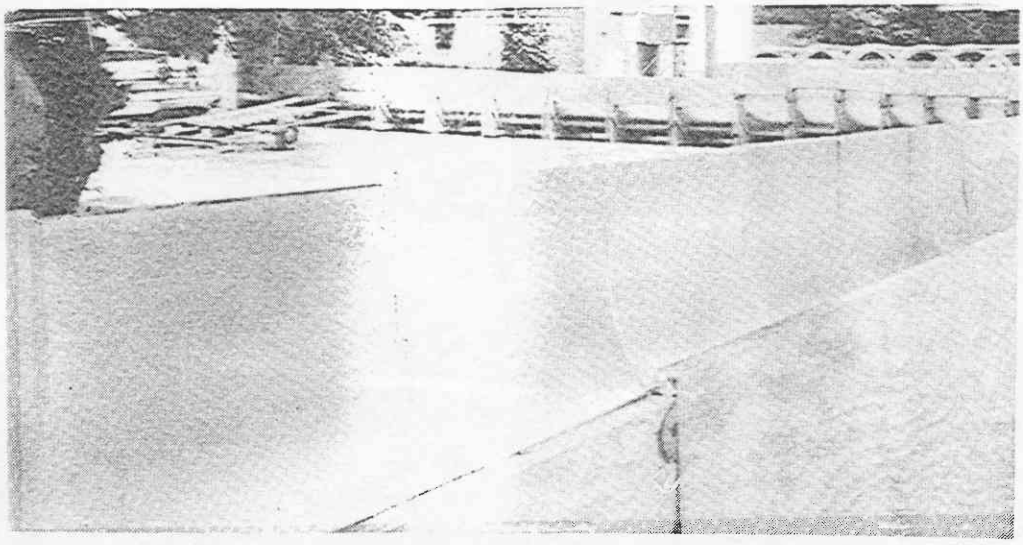


Figure 13. View across the **Aeroduct** ROW and the North straightaway.

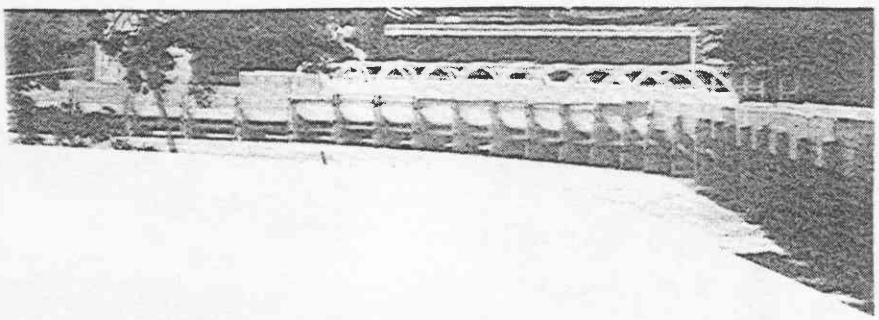


Figure 14. View of 220 degree cylindrical 90 degree **Aeroduct** curve sections to allow "banking" of the **Aeromobile 17** at speed.

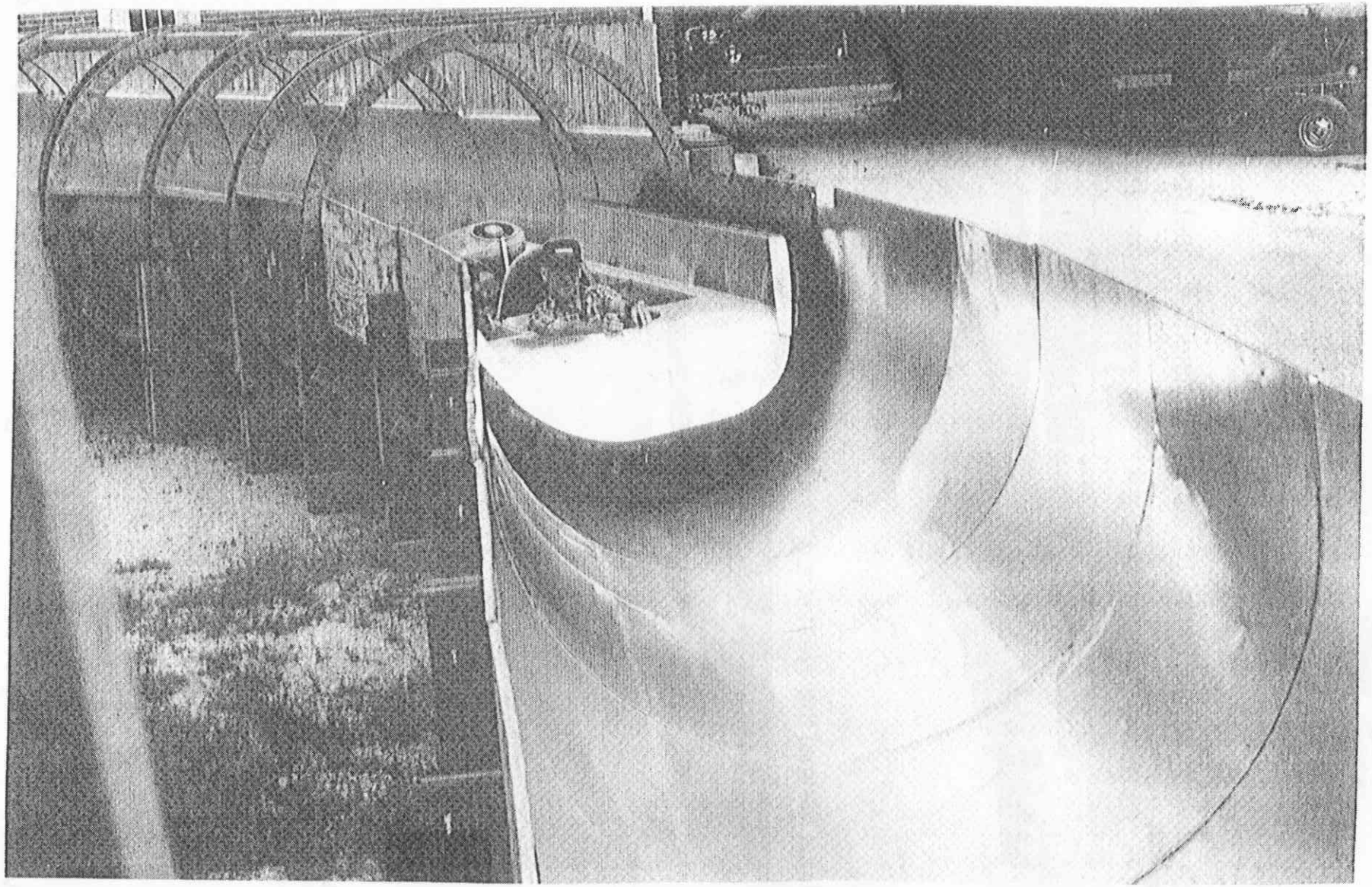


Figure 15. **The Aeromobile 17** moving frictionlessly at speed with thrust from a slight tilt of the **Gimbal Fan** on the curve of the **Aeroduct** ROW. It is shown it slightly banked by centrifugation on the turn.

limit to the diameter of any specific **Aeroduct**. Any size tube/groove can be specified depending on its mission. They can be electric powered.

1. Automation of Aeromobiles in Aeroducts.

When the technology has advanced beyond the shuttle horizontal elevator stage, wider, more diverse deployment is feasible. The ROW's will have "Y" intersections to allow programmed automated diversion of the **Aeromobiles** by lateral thrust of the **Gimbal Fans** to the right or left tine of the intersection fork. (See figure 16 and 17.)

All travel origins and destinations will be from formal stations only, like those of vertical elevators. These stations will have digital addresses, with all arrivals and departures from stations inside homes,schools, airports, malls, stadia, and office buildings, etc. (See Figures 18., and 19.) Greater personal security will be another legacy, of **Aeroduct** automation in **The Air Cushion Transportation Century**.

Any station in the System can be reached from any other station. Each "Y" intersection will be electronically digitally identified, "0" for the right tine, "1" for the left tine. Each station will have both signs and electronic I.D.'s on the vehicle dashboard. The computer program will serially program the vehicles enroute to select the programmed 0 or 1 digital route to go from one station to any other station in the System. It will be possible for anyone to punch in the digital code of his or her destination, the requested time of arrival, and the computer will program the routing through multiple "Y" intersections to reach the desired station.

The private or public stations, will be indoors or under shelter. The doors of the station are more like vertical elevator doors. Both the vehicle and the station doors open and close simultaneously. The vehicle doors are on both sides of the craft, and right or left vehicle doors open on which ever side the station doors appear. The vehicle floor and the station floor will be flush and level. The door is open overhead so that passengers walk in instead of stooping, bending, and twisting to pull their feet in as is necessary in entering automobiles. Likewise, a stroller, or a wheel chair can enter and emerge effortlessly. One other difference in the **Aeromobile** interior is the need for wheel chair or stroller anchors and safety belts to secure the occupants. These passengers will not need to transfer to or from a wheel chair, a child seat, or a stroller. And there will be no need for folding and storage of their equipment, a considerable improvement in convenience and time saving. The automated craft arrives at, and leaves from, only a secure station, whether in the private home, the school, office building, shopping mall, stadium, etc.

2. The Case for Pursuing Air Cushion Vehicles in Guideways.

It is not obvious that a sea change must be made in our ancient modality of ground transportation? (Reference 4, *Asphalt Nation.*, Jane Holtz Kay.)

1. We cannot continue to destroy the planet and its atmosphere with

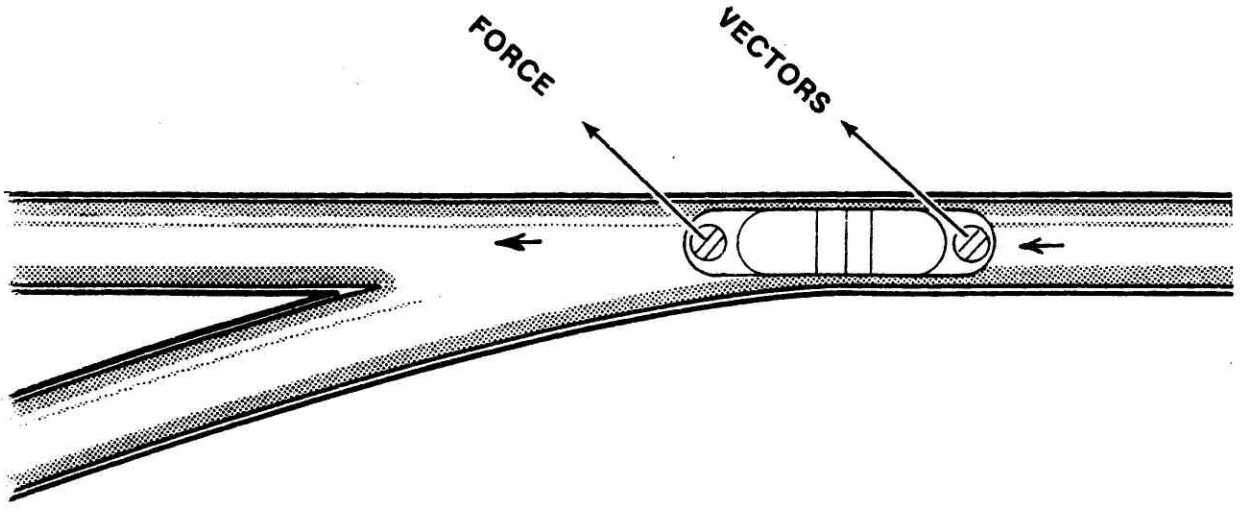


Figure 16. Plan view drawing of the "Y" intersection which will allow conversion of the shuttle only, "horizontal elevator", **Aeroduct System** to a digitally programmable, switchless automated system with multiple destinations.

SIDE VIEW, STEPPED AERODUCT FOR GRADE CLIMB AND DESCENT

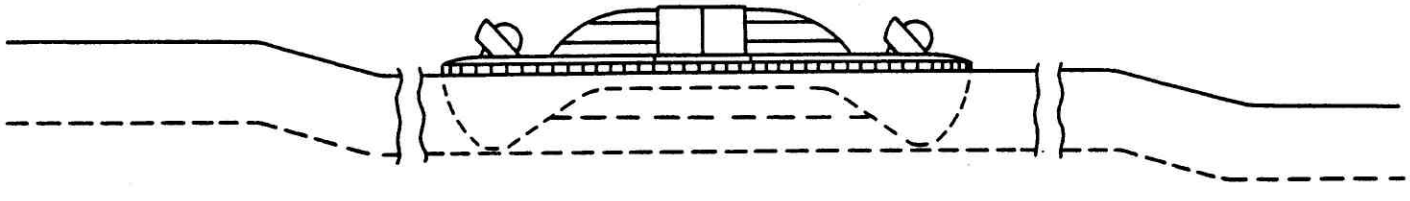


Figure 17. Plan view of **Aeroduct** steps enabling **Aeromobiles** to climb and descend grades with minimum thrust in either direction. Each step riser will smoothly ramped and will be less that half the skirt height to allow the ascending craft to plane over a step, then come up to full cushion height before encountering the next step. The "treads" of the steps will be sloped about 1% uphill, so that descending **Aeromobiles** will need some forward thrust to go downhill. This will prevent "tobogganing" or luge like velocity of an **Aeromobile** on a down hill stepped **Aeroduct**.

fossil hydrocarbon fuels only because there are no "gas Stations" for less polluting fuels. Cars and trucks contribute a large percentage of the atmospheric CO2. Consider only the atmospheric damage of the cumulative effect of burning fossil fuels in cars, trucks, tractors, trains, etc. In this new System, we can immediately install natural gas fuel filling stations which will cut CO2 emissions to half that of gasoline and diesel. In the post automobile, **Air Cushion Transportation Century**, the new vehicles can be fueled by the ultimate zero polluting, solar generated hydrogen.

2. At 40 million dollars per new lane mile, we cannot lay any more concrete or asphalt. We must stop extending and continuing world wide local ecologic surface destruction by bulldozing roads through environmentally sensitive tundra, rain forests, etc., in developing countries and everywhere else. Where roads go, **Aeroducts** can also go. But **Aeroducts** can go where roads cannot economically go. The tube or groove ROW can be elevated, superimposed over roads, or over the median of Interstates, or go cross country. **Aeroduct** capacity can be greatly increased by adding more tubes or grooves stacked in multiples, one above the other. Elevation is cheap and appropriate for **Aeroducts**, but, it is horrendously expensive to elevate and maintain roads. It is also cheaper to bore cylindrical tunnels with minimal lining for **Aeromobiles** vs. tunnel road beds for wheels on roads or rails. The inescapable conclusion in the absence of other alternatives, is that to enormously increase traffic lane miles, we must go on air cushion vehicles in guideways.

3. Air cushion support of vehicles and the elimination of wheels simplifies and reduces the cost of the vehicles by an order of magnitude. The air cushion vehicle is one of the simplest of all motor vehicles. **The Twin Gimbal Fan Aeromobile** has only two moving parts, the two **Gimbal Fans** with associated servos, etc., the chassis, and the skirt. Air cushion suspension eliminates not only the wheels, but all automobile running gear, four tires, brakes, bearings, suspensions, shocks, axles, differential, drive shaft, transmission, plus steering quadrant, ball joints, etc. On air cushions, there will be near zero rolling friction between vehicles and their rights-of-way, increasing efficiency many fold.

4. Air cushion suspension decreases the load factor on the ROW by a factor of 200 in automobile tires, and by a factor of 600 in truck tires. The ROW can, therefore, be far cheaper to build. The technology of paved roads has improved little since the Appian Way, and is without prospect of significant further improvement. Unlike our hand-built roads and bridges, these grooves or tubes can be mass produced, prefabricated and taken to the site and quickly erected.

5. Cars are merely wheel chariots at the pinnacle of technologic development, essentially still horseless carriages. We got rid of the horse, it is time for the carriage to go! Air cushion support of vehicles obsoletes wheels on roads and rails for most commuter type travel. No new streets, roads, or rails need be cut though the surface since existing ones can have **Aeroducts** superimposed, or elevated above them. The ROW's can also be readily multiplexed, doubled, tripled, etc., in capacity by stacking them one on another, for great increase in ROW capacity, impossible for roads or rails.

6. The **Aeroducts** destroyed by earthquakes, in contrast to surface

or elevated roads, can be quickly replaced. Floods moderate to severe will be unlikely to affect the elevated **Aeroduct** ROW's. Without wear, or pounding wheels, the durability and maintainability of the ROW's should be far more economical, with no annual delays from "road" construction.

7. The current thinking in U.S. is "Intermodal" transportation, attempting to connect all modes of transportation by transferring to and from car, train to bus, to ferry, to airplane, etc., at various intersecting points. I submit that if there is one transportation modality which can perform every transit function on the same rights-of-way, without multiple transfers from one modality to another and the inevitable delays, Intermodal is "outmoded". With the **A-A System**, there can be, on the same elevated groove or tube **Aeroducts**, a mix of private **Aeromobiles**, ACV cabs, buses, heavy freight, and mass transit vehicles. Air cushion vehicles in guideways, can be both universal and "unimodal".

8. Air cushion vehicles in guideways allows for absolute, perfect guidance and unerring automation despite sleet, snow, fog, rain, etc.

3. The Case for Automation of Ground Transportation. (For complete automation, the Aeromobile-Aeromobile System has no viable equivalent.)

There is finally wide recognition that automation is necessary. There is a heavily funded effort by government and private industry attempting to automate cars on roads. This is called called **ITS**, or **Intelligent Transportation Systems**. (References 2, and 3.) While it is possible to automate wheels on dry roads, automation will be no better than human control in sleet or snow covered roads. This hugely expensive program can result only in incremental gains in traffic volume, and only in good weather. **ITS** fails with wheels on roads because of inconstant, unreliable guidance and braking in all surface conditions. More importantly, **ITS** does nothing to add more traffic capacity in additional lane miles. **ITS** does nothing to relieve the horrendous parking crisis. The projected increase in existing road lane utilization by **ITS** will be small relative to the massive cost of the program. A Sea Change in ground transportation is imperative!

Amphibious air cushion vehicles in groove or tube ROW's are perfectly guided, cheap, weather indifferent, and absolutely precisely automatable, and rapidly replicated, multiplexed, and superposed over other ROW's. In **The Air Cushion Transportation Century**, it is anachronistic to attempt **ITS** automation of wheels on roads. Wheels on roads, human or computer driven, have failed, will fail, and have no prospect of universally solving our gridlock, delays, highway fatalities, injuries, pollution, the parking crisis, and the high cost of owning and maintaining cars and roads.

However, the huge advance in computer science by the **ITS** program for steering, locating, braking, timing, routing, and spacing automobiles on roads will be very easily adapted to air cushion vehicles in guideways. The **ITS** hardware and software is a

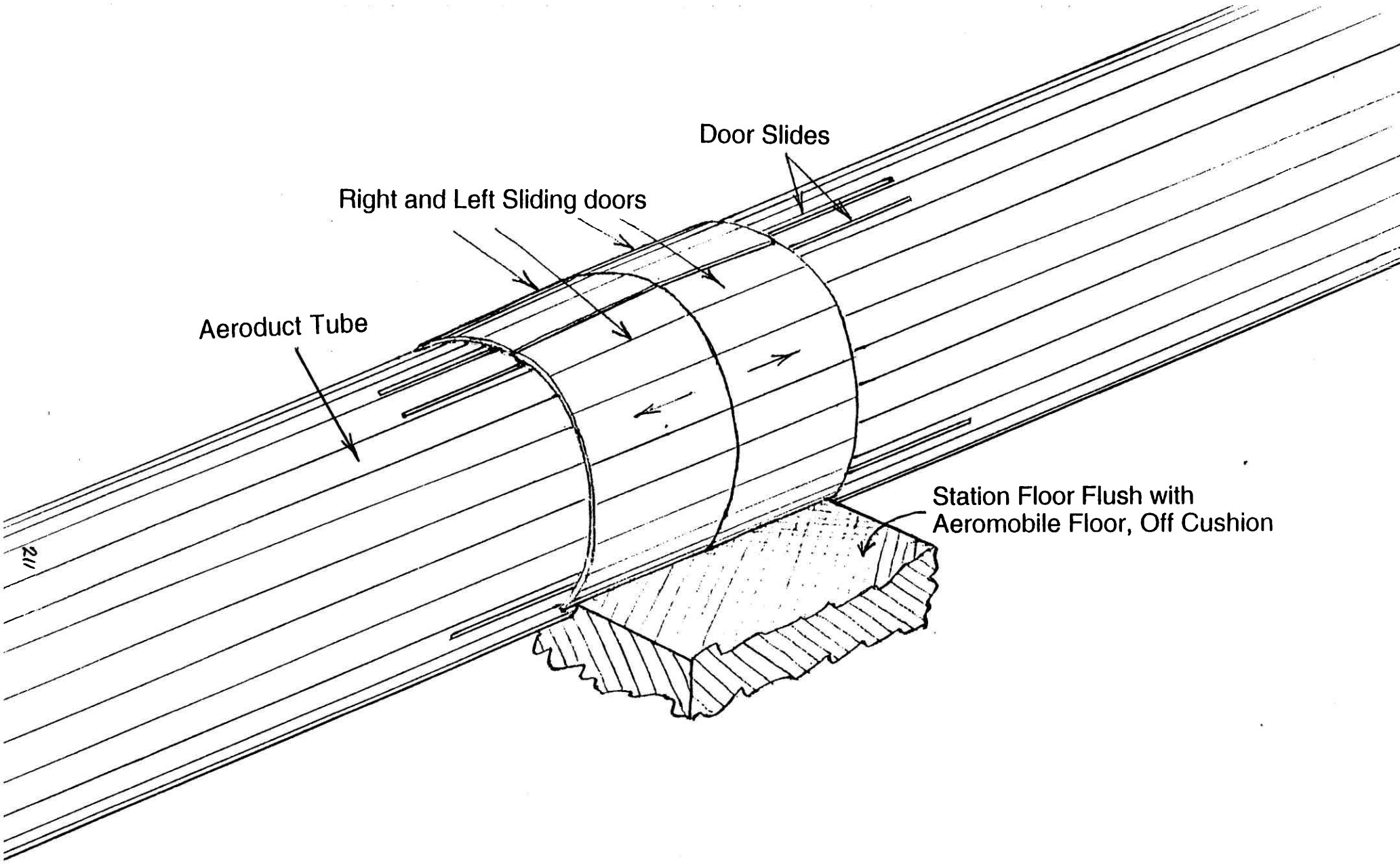


Figure 18. Exterior of proposed tube type **Aeroduct** Station with Doors closed.

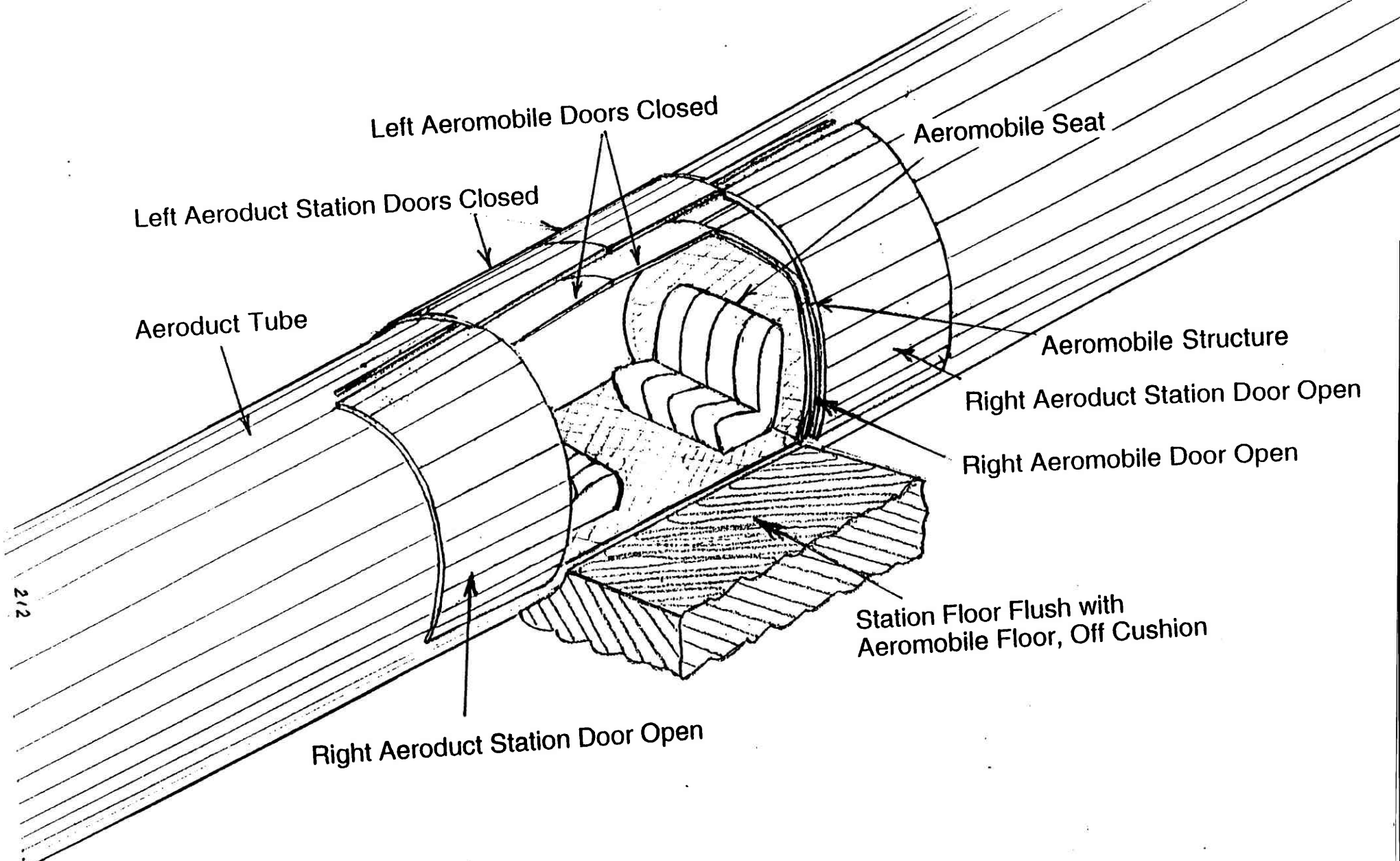


Figure 19. Proposed **Aeroduct** Station Showing Interior of **Aeromobile** off Cushion, with both Right Station and Right **Aeromobile** Doors Open.

head start, and can be readily converted to the same functions with far greater potential in the **Aeromobile-Aeroduct System**.

III. The Aeromobile-Aeroduct System Should be Developed and Deployed because: As shown in the road casualty statistics, human control of wheel vehicles, with surface weather and human frailty as factors, has abysmally failed. Automation with perfect guidance, is, therefore, not optional for personal and mass ground transportation, for the following reasons, it is imperative!!

1. In 1996, on U.S., often on weather treacherous roads, by human driven vehicles, there were, 43,000 deaths and injuries of many thousands more. Automation of all vehicles is the only viable alternative. When there is an automated, all-weather system of ground transportation, it is unacceptable, not to pursue that alternative.

2. It is unacceptable to continue to waste two billion labor hours per year in traffic tie-ups. total automation by programming all trips can be either done in advance or at the time of departure. There is a prospect of vastly increasing human productivity and free time as a result of time made available by shorter travel time. In addition, people can work or play enroute. The commuter will be assured in advance, with certainty, of his time of departure and arrival, at the programmed station.

3. One of the less obvious, but highly significant benefits of automation allows elimination of parking places, and square miles of parking lots in every city, everywhere. This is not only a tremendous ecologic legacy, of **The Air Cushion Transportation Century**, but a solution to one of the most frustrating, maddening, and costly concerns of automobile travelers and the proprietors of their place of destination. Automated vehicles can return to the owners one parking space at home. Alternatively, automated parking facilities can be built locally for those traveling distances too far for economical return of the craft to the home parking space. These automated parking facilities will be few in number, needed only by distant travelers. They can be underground, taking up zero land space. They can be high rise requiring a small fraction of the area of existing parking lots. Rental automated "cab" vehicles can return to their staging place or go to the next fare station. The personal or public vehicles can be electronically recalled to whatever station location the person is located at the time of return. Such services are not even remotely possible for cars on roads.

4. All **Aeroducts** can be elevated above vulnerable, non relocatable people and vehicles at ground level. In air cushion ROW's, there need not be any clash between vehicles, children, pedestrians, bicycles, deer and other animals wild or domestic. All travel will be from the second story of a home, office, mall, etc., leaving the ground level to all those most subject to injury.

5. The **Aeroducts** will cross each other on different levels without intersections, above, across, or parallel to, roads and rails. With automation, there will be no stopping between origin and destination in any trip to or from any station. The "throughput" or efficiency of an automated ROW with higher block to block, non stop speeds, vehicle spacing and timing, should be, conservatively, ten times better than manually driven, or automated cars on roads. The **A-A System** will pay for itself in

time saving alone.

6. **Aeroducts** can be assembled quickly and cheaply like "erector sets", with all prefabricated elements, the first installation can be fast and cheap. If damage occurs from earthquake, mud slides, etc. they can be replaced in hours rather than days or weeks as we suffer with annual or catastrophic road rebuilding.

7. No small economy of automation is the elimination of all of the headlights, tail lights, turn signals, rear view mirrors, backup lights, parking lights, wind shield wipers, squirts, rear view mirrors, in the vehicles. There is no need for ABS, cruise control, etc. All gear for driving would be replaced by onboard and central control computers with software to allow automated route programming in the vehicle or remotely with electronic wireless data transfer. The cost of this basic electronic package is far less than that long list of automotive components they replace. In a car, there are great many things to buy, to maintain, and to fail, the **Aeromobile** is manifestly simpler and cheaper. All of these eliminated parts will reduce not only the cost, but the mass of the craft, a great saving in energy for acceleration and braking.

8. The chassis of the **Aeromobiles** can be made of 90% recyclable materials. The skirt is of urethane-nylon, or neoprene-nylon and represents about 10% of the vehicle weight. The interior will be similar to the auto interior with seats, interior lighting, stereo set, etc. What can be added optionally will be a television set, personal computer, telephone, or other niceties as plush as the owner wants to occupy the now driverless "passengers" in this totally automated transportation system. One will almost never see the exterior of his Aeromobile anymore than one sees the outside of an automatic elevator. (Figure 16.) A mass produced **Aeroduct Aeromobile** would cost about half of what a car costs to buy, operate, and maintain.

9. With automation, there is no danger of collisions, head-on, rear enders, or "T bone" broadside crashes in **Aeromobiles** in **Aeroducts**. There is no need for all the structure for energy absorption, air bags, crush space, massive bumpers, side bracing, etc. The elimination of all this additional automotive gear, and structure further lightens and cheapens **Aeromobiles** over automobiles, and will, result also in even further energy saving in reduced power for lift, acceleration, and braking. An **Aeromobile** is a hollow shell of the complex automobile, but in **Aeroducts**, it provides tremendous, unique and unprecedented capabilities over all other transportation systems.

IV. Conclusion: No other System, existing or proposed, can match the multiple, life saving and life enriching qualities, the comfort and convenience of automated air cushion vehicles in guideways. Nor can any other system match the economy, efficiency, safety, security, low pollution, all-weather operability, accessibility to the disabled, the ability to replicate the ROW's ad infinitum, and totally solve the parking crisis. These are the singular advantages of The Aeromobile-Aeroduct System of Automated Transportation. It is the commuters' sole alternative, and it must be pursued.

William R. Bertelsen, M.D., FCASI

V. Addendum:

Possible Questions about this totally new Air Cushion Modality of Guided, Automated, All-Weather Ground Transportation:

1. (a). What about stalling of an **Aeromobile** in the groove ROW by power failure, or other causes? Answer: The probability of failure of the mechanically and electronically simple **Aeromobile** in and **Aeroduct** is a tiny fraction of the probability of that of the vastly more complex automobile in which a flat tire can disable it. **The Twin Gimbal Fan Aeromobile** unlike cars, has twin engine reliability, and will fly on either engine. In failure of one power system, the craft can be diverted to another exit. Another unobvious benefit of total automation of all traffic is that in any emergency, that blocked leg of an ROW can be electronically commandeered for sole access by the appropriate emergency vehicles. All other traffic will be diverted and rerouted around the occluded ROW. It is recommended that there be multiple redundant ROW's parallel to, above, beside, or under major ROW's for all emergencies, including fire, police, paramedics, and the diversion to it of faltering vehicles. Note: Suddenly coming off-cushion through power failure, etc., at speed enroute is not dangerous. The craft slowly loses cushion pressure at speed, skids to a stop, and rests on the surface of the ROW.

1. (b) But, in the event of a stalled craft becoming stuck in the ROW, with automated traffic, and **ITS** computerized spacing, braking, locating, and diverting following **Aeromobiles**, the potential for collision is minimal. Again, the **A-A System** collision risk must be compared to the dismal collision statistics of human driven wheels on weather treacherous roads.

1. (c). Despite the low probability of stalling in the ROW, how would a disabled **Aeromobile** be retrieved? Answer: If the diversion of the **Aeromobile** fails, and all other traffic is diverted or stopped, and the craft is stuck in the groove ROW, air cushion "tow trucks" can be dispatched to inflate the cushion of the stalled craft, and push it to a service facility, or other destination. All occupants of the stalled craft will have continuous contact by dashboard display, cellular phone with the central network, can communicate with any other parties, and can be kept advised o f the status of help. By comparison, consider the awkwardness the security risk, and the delay, of calling of a tow truck for a stalled car on a road, in unknown territory . The rescue of a stalled **Aeromobiles** in ROWs is fast, safe, secure, certain, and extremely rare.

3. What about heavy snowfall filling the groove? Answer: Open grooves will collect snow, but no snow plowing is necessary, no salting, no cindering, etc., are needed. In high traffic legs of the ROW's, the passing **Aeromobiles** will blow out the snow as it falls keeping the ROW open. In low traffic ROW's, service **Aeromobiles** can simply patrol that leg to keep the snow blown out and prevent its accumulation. Snow accumulation in **Aeroducts** is preventable, infinitely cheaper, and far less environmentally destructive in snow, ice, sleet, compared to precipitation management of roads. In tube **Aeroducts**, there will be no precipitation.

4. (a) What about grade climbing and descent in frictionless groove ROW's? Answer: The installed power in **The Gimbal Fans** allows for climbing and descending all railroad grades. In hilly areas, there are several design choices to get

up and down grades of railroad percentage. One method is that the economy of the structure allows spiraling the of dual one-way thin sheet metal or composite ROW's up and down heights. There can be "Y" intersections at any point in the spiral for entering and exiting craft to various destinations.

4. (b). For long, steep grades, the height of the air cushion skirt allows "step climbing". **Aeroducts** can be built with steps to enable **Aeromobiles** to climb and descend steep grades with minimum thrust in either direction. (See Figure 17.) The ROW will be designed to have each step "riser" smoothly ramped at less than half the skirt height to allow the ascending craft to plane over a step, then come up to full cushion height on the "tread" of the step before encountering the next step. The tread of the steps should be sloped slightly uphill to prevent "tobogganing" or luge-like velocity on a down hill stepped **Aeroduct**. The descending **Aeromobiles** will, therefore, need some thrust for propulsion to go downhill and "climb" the 1% or so grade of the uphill sloped tread of the steps. The ascending **Aeromobiles** will, in contrast, need little thrust to climb steep uphill sloped stepped grades.

5. What cruise speed will **Aeromobiles** in **Aeroducts** attain and maintain? Answer: As with the amphibian ACV's, the top speed of the craft is subject to aerodynamic lift at speed greater than 30 to 60 M.P.H. The Air cushion vehicle center of lift, (C.L.), at hover and at low speed is at its' geometric center. But as speed rises, the craft becomes an airfoil and is subject to aerodynamic lift which is typically centered a 25% back from the leading edge of an airfoil. The ACV at higher speeds as an airfoil, the C.L. shifts forward causing pitchup of the nose of the craft. All aircraft speeds will ultimately be possible for ACV's in guided ROW's, and there are many ways to overcome this effect. But the groove traveling **Aeromobiles** will typically be, at first, confined to speed less than 60 M.P.H. Consider that in traffic, the automobile sometimes averages 5 M.P.H. with multiple stops and go's. For the moment, below aerodynamic lift speeds of ACV's in guided ROW's, going programmed non-stop from origin to destination is adequate, and is a quantum leap over the block to block speed of cars on roads.

6. What about the noise? Answer: The present noise level of our amphibious **Aeromobiles** with internal combustion engines, without any attempt at noise suppression is no greater than that of a passing semi truck. At low r.p.m. of the engines, to get up on cushion the noise is tolerable for persons onboard and nearby. As acceleration in any direction raises engine speed, the noise rises, but inside the cab, it is tolerable for the passengers. As the craft moves away from the bystanders, the noise quickly fades with distance. with high speed **Aeromobiles** in elevated **Aeroducts**, the instant of noise generation to local residence will be brief, and less than that of present auto/truck traffic. Elevation of the grooves also focuses the noise upward making it even less objectionable than living next to a busy highway. In tube **Aeroducts** the noise is contained and even less problematic.

Great strides have been made in both sound absorption in ducted fans by jet engine designers, and by electronic sound cancellation. We have not reached the point that requires such measures. With conversion to electric motors, the noise will be even less.

Aeromobile, Inc.

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