ASNE Advanced Vehicle Conference
Arlington VA, USA, June 1989

The Prediction of Resistance of Surface Effect Ships

Heiko Oehlmann, MTG Marinetechnik GmbH, Hamburg, GERMANY
John C. Lewthwaite, Consultant Naval Architect, Fareham, Hants., ENGLAND

ABSTRACT

MTG Marinetechnik in Hamburg has designed a large SES, called SES-700 Fast Test Craft. A 5 m long model of this design has been extensively tank tested at the David Taylor Research Centre (DTRC) in Washington D.C., USA. In addition, sea-keeping data for a number of UK SES craft have been purchased from Hovermarine International and analysed in order to extend the data-base with respect to differing hullforms and size variations.

In this paper, the results of a study into the resistance of various SES in both calm water and in head seas, are presented. Generalized methods of prediction of resistance have been developed which can be applied to new designs. Several theories of the individual resistance components have been incorporated into a computer program named SESDRAG, and examples of the output from this program are given for a new SES design.

THE PREDICTION OF RESISTANCE OF SURFACE EFFECT SHIPS

by Heiko Oehlmann (MTG Marinetechnik GmbH, Hamburg, Germany)
and by John C. Lewthwaite (Consultant Naval Architect, Fareham, Hants., England)

1. INTRODUCTION

During the past few years, MTG Marinetechnik in Hamburg has been designing a large steel hulled SES (called the SES-700), under a contract from the German MoD. A 5 m long model of this design has been extensively tank tested at the David Taylor Research Centre (DTRC) in Washington D.C., USA. The tests have covered measurements of the resistance and motions of the model in both regular and irregular headseas, with variations in speed, displacement, lift setting etc. These have been analysed firstly to enable predictions of the performance of the full-scale craft to be made, and also to build up a technology base for further SES design developments. In connection with the latter, sea-keeping data for a number of UK SES craft have been purchased from Hovermarine International, to extend the data-base with respect to differing hullforms and size variations.

The results of a study into the resistance of these SES in both calm water and in head seas, forms the subject of this presentation. Generalized methods of prediction have been developed which can be applied to new designs in order to determine the projected speed and also to check on propulsor loading, so that cavitation limits can be considered. These theories have been incorporated into a computer program named SESDRAG, and examples of the output from this program are given for a new SES design.

2. BACKGROUND DATA

2.1 SES-700 Model Tests

The general arrangement and overall dimensions of the 60 m long SES-700 are given in Figure 1 and Table 1. The design was fully described by Knüpffer et.al. (1989).
A 1:12.4 scale model was constructed in 1986 for use in towing tank tests.

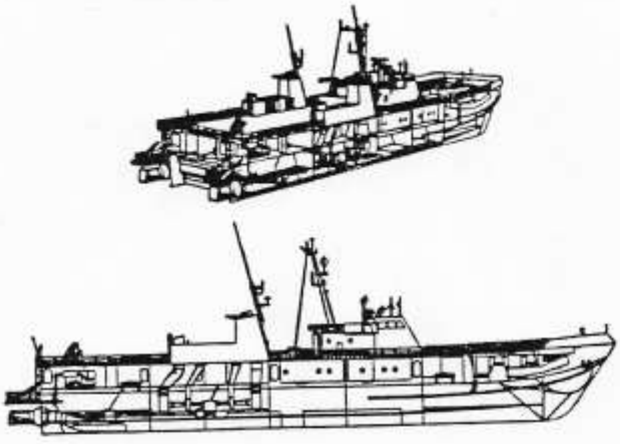

FIGURE 1: SES - 700 GENERAL ARRANGEMENT

TABLE 1 - SES-700 MAIN CHARACTERISTICS

Length between perpendiculars	59.55 m
Beam moulded	16.10 m
Draft hullborne	2.85 m
Draft cushionborne	0.95 m
Level of wetdeck	4.40 m
Full load displacement	720 t
Payload	30 t + 50 t fuel
Hull material	high tensile steel
Cushion length	53.30 m
Cushion beam	11.30 m
L/B cushion	4.72
Buoyancy fraction (cushion/sidehulls)	83.1 % / 16.9 %
Speed (calm water)	50 kn (plus)
Complement	up to 18 Persons

The model was tested at the David Taylor Research Center (DTRC) Washington D.C., in their high-speed test facilitiy, see Figure 2. Testing was carried-out in three phases (Series 1, 2 and 3), in which various aspects of the design and several modifications were investigated over a three-year period.

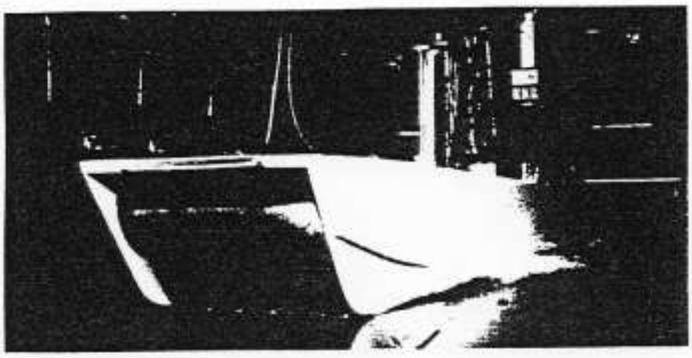

FIGURE 2: SES - 700 MODEL TESTING

The calm water performance was established over a speed range up to 60 knots, at various lift system settings, corresponding to changes in the hull buoyant fractions and at three craft weights.

The overwave resistance was measured in both regular waves and in irregular headseas conforming to JONSWAP type wave spectra, representing typical conditions in the central North Sea. Tests were made in a range of significant wave heights, upto a maximum approaching the depth of the cushion. Again variations in speed, lift settings and craft displacements were investigated.

2.2 Hovermarine Craft Data

Seakeeping information for three UK types of SES were purchased from Hovermarine International some years ago. The craft were as follows:

1. The 60 m long Deep Cushion Craft (DCC) design which was tank tested at a scale displacement of 500 t.
2. The 27 m long HM-5 craft. Data from trials and model tests at displacements between 76 and 100 t.
3. The 16 m long HM-216 craft. Data from trials and model tests at a displacement of about 20 t.

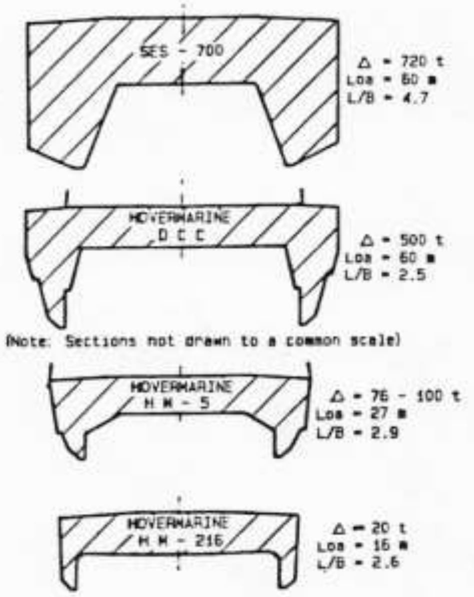

FIGURE 3: COMPARATIVE MIDSHIP SECTIONS

Comparative midship sections of these types, including that of the SES-700 are shown in Figure 3. As can be seen the hullforms and the cushion length-to-beam ratios vary considerably.

The seakeeping data included measurements of the resistance in conditions varying from calm to wave heights approaching cushion depth. Wave spectra generally conformed to the JONSWAP type. Regular wave test results were available for the DCC and some for the HM-5.

3. RESISTANCE STUDIES

3.1 General Requirements

The objectives of the study of SES resistance were to be able to predict the variations in performance due to:

1. Hullform and cushion geometry
2. Lift setting (ie. hull buoyant fraction)
3. Displacement
4. Wave height, including wave spectrum differences

At the present time the theory is limited to headsea operations, since the main source of the data was derived from tank tests. We also wanted to make predictions in either full-scale or model terms, with the appropriate skin friction corrections.

3.2 Hullform definition

The sidehull form is defined at five equally spaced stations between the transom (1) and the sidehull forefoot (5), with station (3) being amidships - see Figure 4.

At each station the form is defined by five parameters controlling the lower sidehull geometry, together with three other hull dimensions (cushion beam, cushion depth and weather-deck height). These terms define the sidehull form reasonably adequately and are used to calculate the hull immersed volume, wetted area and water-plane area for any specified draught. It has been found that the integration procedure gives values within a few percent of those determined from the line plan.

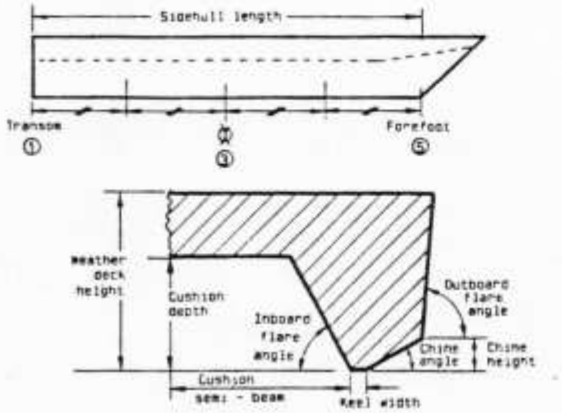

FIGURE 4: SESDRAG HULL DEFINITION

It is assumed that there are no significant changes in hull sections above those given, or that a mean section can be adequately defined to include these. It is also assumed that the wet deck is flat and parallel to the sidehull keel line.

3.3 Lift Setting Definition

SES craft are able to adjust their draught by control of the speed of the lift fans. The lift setting is defined by the proportion of craft weight carried by the sidehulls, ie. the buoyant fraction. In calm water a full-hover condition (typically 15% buoyant fraction) is normally used to obtain minimum resistance, but partial lift settings can be used at lower speeds for special requirements.

In overwave operation it has been found that reductions in craft motions can be obtained by running with increased draught giving higher buoyant fractions, (typically around 40%).

In the extreme case, craft can of course operate in the boating mode with the hulls carrying the full weight where the buoyant fraction is 100%.

4. RESISTANCE COMPONENTS

The total resistance has been sub-divided into seven main components as listed below:

Calm Water
- Cushion wavemaking resistance
- Sidehull frictional resistance
- Sidehull wavemaking resistance
- Sidehull spray drag
- Seal drag
- Aerodynamic drag

- Additional drag in headseas

4.1 Cushion Wavemaking Resistance

This has been based on the classical theoretical wavemaking resistance of a moving pressure field over water. In particular an analysis by BARRAT (1965) is used. Craft operation is only considered in deep water. The resistance is found to be dependent upon the cushion pressure, length to beam ratio, and the Froude number. The secondary hump at a Froude number of about 0.35 is represented although at a smaller magnitude than that theoretically predicted, since wave steepness effects have been shown to limit this.

It should be noted that this wavemaking term is that due to the cushion depression alone and does not attempt to include the sidehull wavemaking. Sidehull wavemaking is treated as a separate term since it is recognized that the slenderness of the hulls will result in different wave formations than those produced by the cushion.

4.2 Correction due to Planing Lift

It has been found that lift forces can be generated by the sidehulls when running at high speeds. The lift force can be calculated from planing boat theory [MURRAY (1950)], using the lower sidehull geometry together with the speed, to determine the lift coefficient (typically 0.1 to 0.2).

This lift force is then assumed to off-load the cushion, lowering the cushion pressure and hence reducing the wavemaking resistance. This effect is only significant at high speed with full lift, where the cushion pressure is high, and the sidehulls only carry a small proportion of the craft weight. It can therefore be assumed that there is little change in the sidehull immersion or the corresponding sidehull drag components.

4.3 Sidehull Frictional Resistance

This is based on normal ship resistance calculation procedures. The wetted area is calculated for the selected draught, together with the appropriate Reynolds' number and skin friction coefficient from the 1957 ITTC line.

The wetted area is assumed to be constant at high speed. Model tests have shown that this is a reasonable assumption for Froude numbers above 0.45. However, at lower Froude numbers where the craft operates around the secondary and tertiary wavemaking humps, an increase in wetted area is assumed to occur. A 50% increase is applied at high lift settings (ie. full-hover), but this is reduced at lower lift. This correction is based on measurements made during model tests.

4.4 Sidehull Wavemaking Resistance

The wavemaking resistance of the sidehulls is based on some un-published test data on high speed, low displacement slender hulls. At high slenderness ratios (ie. sidehull beam/length) the data show reasonable correlation with fine hulled ship data for semi-planing hulls [BARNABY (1960)]. At slenderness ratios typical for SES, the values are well beyond those of the monohull data.

The sidehull wavemaking resistance is dependent upon the immersed volume, sidehull length, slenderness ratio and the Froude number. A noticable feature of the sidehull wavemaking data is that the main hump occurs at a similar Froude number to that of the cushion, but is of course based on the sidehull waterline length, so that the hump occurs at a slightly higher speed.

In calculating the sidehull wavemaking resistance, a hull separation term has been introduced based on the ratio of the beam of the cushion to that of the sidehull. A close separation is required (ratio below 4), before any significant interaction occurs. Typical SES beam ratios are normally between 5 and 15.

4.5 Sidehull Spray Drag

In the cushion-borne mode a spray drag term is included in the resistance breakdown, which is dependent upon cushion pressure, sidehull length and is proportional to speed squared. This term is only really significant at high speed, and the output is combined with the sidehull wavemaking to represent the total residual (or form) drag.

4.6 Seal Drag

The final term in the calm water hydrodynamic resistance breakdown is the seal drag which in practice will clearly be dependent not only upon the seal type, but its tailoring relative to the keel line.

As a generalized approach, a contact area dependent upon the sidehull immersion (i.e. draught) and cushion beam is assumed, together with a representative friction coefficient. In full-hover the sidehull immersion is approximately equal to the cushion depression. In partial cushion mode the contact area is increased. In the boating mode it is assumed that the seals can be retracted (ie. zero seal drag).

An allowance is included in the seal drag calculation for spray, seal discontinuities and roughness. The drag is assumed to be proportional to speed squared.

4.7 Aerodynamic Drag Components

The aero drag components are frontal area drag and air momentum drag. Both can be calculated in accordance with classical theory.

4.8 Added Drag in Headseas

Ship theory [MARUO (1957)] suggests that pitching motions have a dominant effect upon the added drag in waves, which is closely proportional to the wave height squared, and largely independent of the magnitude of the calm water resistance.

Resistance Increment Operators (RIO's) can be developed, which when applied to an encountered wave spectrum permit calculations of the added drag in that seaway to be made. In other words the theory of superposition as used in predicting ship motions in irregular seas, can also be applied to the estimation of resistance.

The RIO's have to be developed from regular wave tests where the added drag (ie. the total hydrodynamic overwave resistance less that in calm water) is measured at specific wave encounter frequencies. Regular wave measurements from the SES-700 model tests have been analysed and the RIO curves generated. These were used to predict the added drag in irregular headseas and the results have demonstrated that the above theory is applicable to SES. This is believed to be the first time that this approach has been used in the determination of SES headsea resistance.

In the development of a generalized theory the method of approach has been to attempt to predict the magnitude of the peaks in the RIO curves and the frequency at which these occur. These are based on overall sidehull and cushion dimensions which are likely to be readily available for any SES.

The magnitude of the peak is postulated to be a function of the cross-section (or blockage) of the sidehulls, plus a similar component for the cushion, allowing each to be independently assessed. The encounter frequency at which the peak RIO values occur was related to the natural pitching frequency of the craft determined from the displacement and sidehull geometry. The RIO variations either side of the peak frequency, are defined by exponential equations based on the results of the model tests in regular waves.

The added drag in a seaway can then be derived by multiplying the RIO ordinates with those of an encountered wave spectrum and integrating over the frequency range. The theory is applicable to any wave spectrum at any speed, although at present results are limited to waveheights that do not exceed the cushion depth.

5. COMPUTER PROGRAM 'SESDRAG'

The above prediction methods have been incorporated into a computer program named 'SESDRAG'. This is written in BASIC and can be run on a office-type, IBM compatable micro-computer. The scope of the program is as follows:

- The program covers operations in either full-hover, partial cushion or boating modes. In the case of full-hover, the sidehull immersion is adjusted until the cushion is just sealed (ie. the craft is on tip-toe at maximum lift setting). This is an iterative process which involves several integration runs, before the required balance is achieved. The minimum buoyant fraction is calculated to the nearest 0.1%.

  In the partial cushion condition any buoyant fraction above the minimum value can be specified. In the boating mode all the buoyancy is taken by the hulls and wet deck if necessary.

- For the selected buoyant fraction and hull immersion, the program calculates the cushion pressure, hull wetted area, form coefficients etc. These are then used in the calculation of the resistance components listed in Section 4, over a range of speeds specified by the user.

- In the calculation of the aerodynamic drag estimates of the frontal area and corresponding drag coefficient are made in the program, but these can be over-written if required. The program also estimates the cushion air flow requirements; again allowing an alternative value to be substituted.

- The sidehull frictional resistance is calculated assuming a smooth and clean wetted surface. The program will run in either model or full-scale terms, adjusting the Reynolds' number and other corrections accordingly.

- The added drag in headseas can be calculated in any seastate (eg. JONSWAP, ITTC or Pierson-Moskowitz) or a spectrum defined by the user. It is recommended that the specified significant wave height should not exceed the cushion depth. The craft natural pitching frequency which determines the peak in the RIO curves, is calculated by the program, but an alternative value can be substituted.

6. CORRELATION OF 'SESDRAG' WITH MEASURED DATA

In the development of 'SESDRAG', the program has been validated against available SES model and full-scale trials data. As will be appreciated these are invariably commercially classified, and it is therefore not always possible to release actual resistance values.

An example of the correlation of the calm water resistance of the SES-700 as scaled from the DTRC model tests, with the SESDRAG output is shown in Figure 5. This craft has quite broad lower sidehulls which develop planing lift at high speed as predicted by the program. The magnitude of the resistance change due to this planing lift effect is illustrated in the figure.

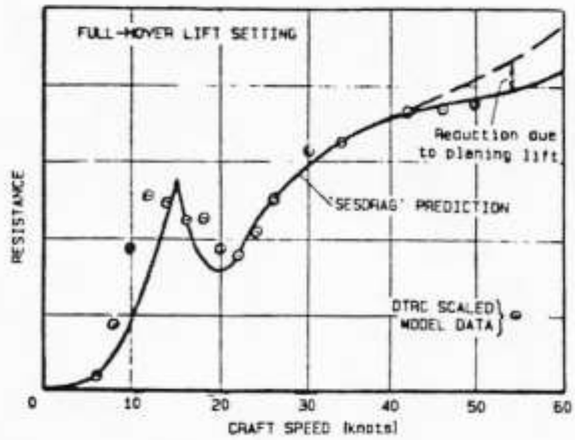

FIGURE 5. CORRELATION WITH SES-700 MODEL DATA.

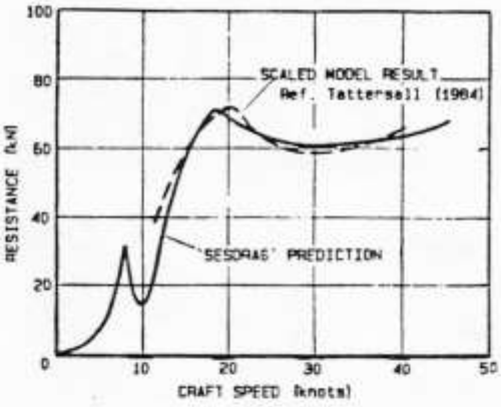

FIGURE 6: CORRELATION WITH HOVERMARINE HM-5 DATA.

A further example of the correlation of SESDRAG with calm water resistance is shown in Figure 6 for the Hovermarine HM-5 as given by TATTERSALL (1984). The close agreement given by the computer program which shows both the primary and secondary humps in the resistance curve, can be seen.

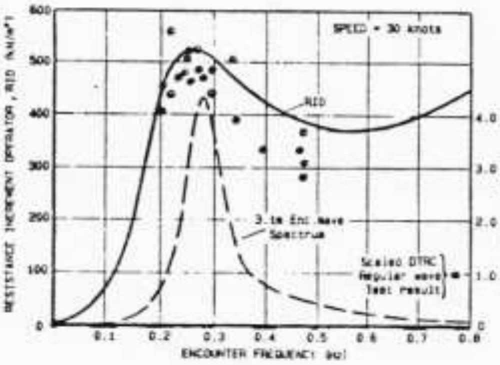

FIGURE 7: SES-700 OVERWAVE RESISTANCE INCREMENTS

As described above, the added drag in headseas is predicted by means of RIO curves. An example showing one of these curves predicted for a speed of 30 knots for the SES-700, compared with results from model tests in regular waves, is shown in Figure 7. The increase in the level of the RIO curve at high frequency, has been found to be necessary to obtain good correlation with the measured performance in small waves. The RIO curve is then integrated with a wave encounter spectrum (an example of a 3.1 m JONSWAP sea state is shown in Figure 7), and the overwave headsea resistance in the irregular sea can then be calculated.

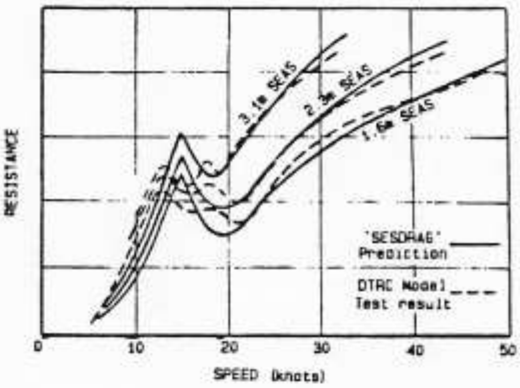

FIGURE 8: SES-700 PREDICTED RESISTANCE IN HEADSEAS.

Predicted overwave resistance curves for the SES-700 operated at a buoyant fraction of 40% are shown in Figure 8, compared with the DTRC scaled model test data for a range of wave heights upto the 3.1 m level. The results clearly illustrate the ability of SESDRAG to closely predict the headsea drag at speeds above the secondary hump (ie. 15 knots). Some refinement in the prediction at lower speeds, appears to be necessary.

Further validation has been made with other results for the SES-700 and for the Hovermarine craft, and in general good agreement has been obtained over the wide range of size, displacement, hullform and cushion geometry etc.

7. SAMPLE 'SESDRAG' OUTPUT FOR A NEW SES DESIGN

7.1 The SES-600

MTG Marinetechnik has recently designed a passenger/car ferry SES, known as the SES-600; see Figure 9. This craft carries 380 pass' and 56 cars at speeds upto 50 knots, with a range of 400 n.miles.

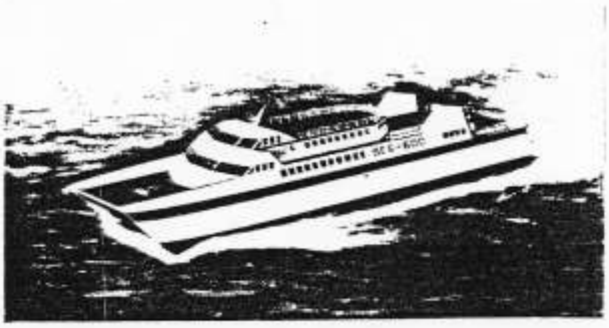

FIGURE 9. SES-600 FAST PASSENGER/CAR FERRY

The craft is 60 m long with a full load displacement of 600 t and has a similar hullform to the SES-700. Model tests have been carried-out in support of this design, and it has been agreed to release some sample predictions from SESDRAG defining the resistance characteristics.

7.2 Calm Water Resistance Components

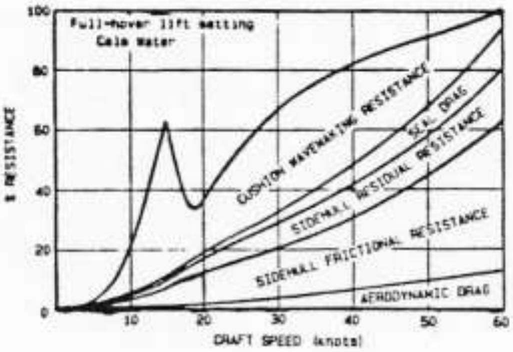

FIGURE 10: SES-600 CALM WATER RESISTANCE BREAKDOWN.

The breakdown of the calm water resistance into individual components is shown in Figure 10. As can be seen, the wavemaking resistance represents a large proportion of the total. This component reduces rapidly at higher speeds.

The secondary hump at a speed of about 15 knots, where again the cushion wavemaking is high, can also be seen. It is important that at this point, the selected propulsor gives sufficient thrust in order that an adequate margin can be provided over the total resistance, so that the craft can accelerate to higher speeds. The propulsor cavitation limits need to be examined at this speed, since the thrust loading will be high.

The second largest resistance component at high speed is that due to sidehull friction, which amounts to 40% of the total at 50 knots. For this reason the requirement to keep the wetted area to a minimum and to maintain the hull in a smooth and clean condition is obvious.

7.3 Variation of Resistance with Craft Weight

The reduction in calm water resistance as the craft weight is decreased is shown in Figure 11, based on full-hover lift setting at speeds of 40 and 50 knots. The reductions are similar in proportion to the change in weight. The reduction is greater at the lower speed since here the cushion wavemaking is a larger fraction of the total and most affected by the weight reduction.

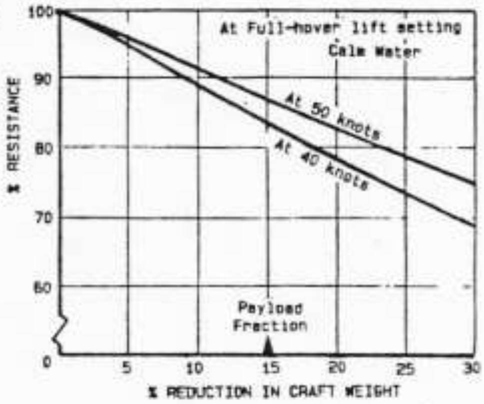

FIGURE 11: SES-600 CHANGE IN RESISTANCE WITH CRAFT WEIGHT

7.4 Variation with Lift Setting

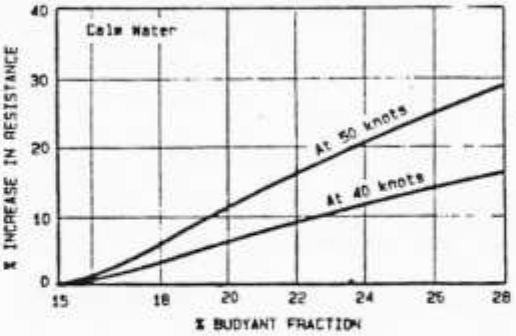

FIGURE 12: SES-600 CHANGE IN RESISTANCE WITH LIFT SETTING.

The increase in calm water resistance as the lift system flow is reduced and hence the buoyant fraction increased, is shown in Figure 12. As might be expected, the increase is more pronounced at higher speeds, where the frictional resistance is a high proportion of the total resistance in calm water.

The increase in resistance at lower speeds is less, and this leads to an interesting situation, as described below.

7.5 Low Speed Optimisation of the Lift Setting

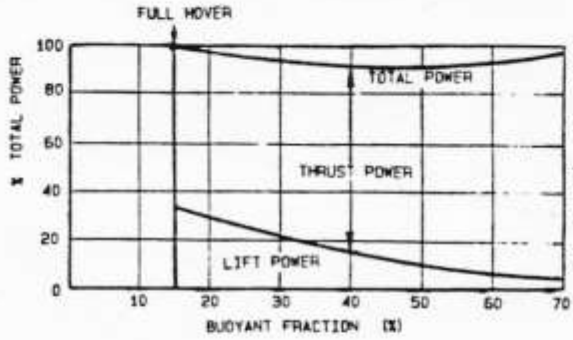

FIGURE 13: SES-600 OPTIMISATION OF TOTAL POWER.

At low operational speeds the rate of increase in resistance and hence thrust power, with increase in buoyant fraction, can be less than that of the decreasing lift power. The situation is illustrated in Figure 13, for a craft speed of 25 knots.

SESDRAG determines the cushion pressure and lift-air flow rate required for each buoyant fraction condition, and hence the lift power can be estimated. A constant value for the lift system efficiency of 75 % has been assumed. The thrust power (assuming 55% propulsive efficiency) increases with buoyant fraction, but the combined total power shows a minimum value at about 45% buoyant fraction, where the total is 10% less than that used at full-hover. This effect has been confirmed by model tests.

7.6 Boating Mode Resistance

With the buoyant fraction set to 100%, SESDRAG can be used to calculate the resistance in the boating mode; see Figure 14. Comparison is made with the full-lift setting case and as can be seen, the craft has a lower resistance when boating at speeds upto 15 knots. The main reason for the higher resistance when in full-hover is the cushion wavemaking, which is larger in comparison with increased skin frictional resistance when hullborne.

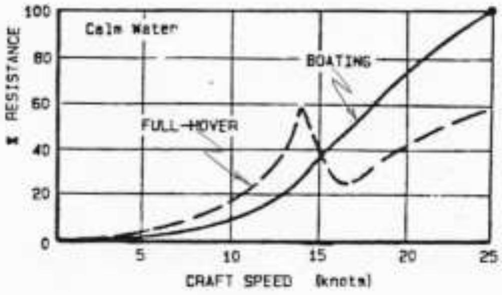

FIGURE 14: SES-600 COMPARISON BETWEEN BOATING AND CUSHIONBORNE RESISTANCE.

Additionally when cushionborne power has to be applied to the lift system and when comparison is made on a total power basis, the cross-over speed will be above 15 knots.

7.7 Resistance in Headseas

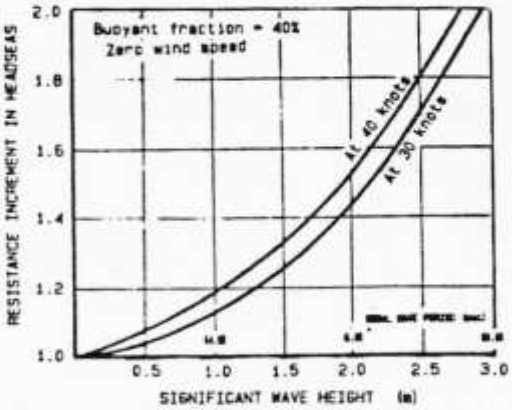

FIGURE 15: SES-600 RESISTANCE INCREMENT IN HEADSEAS

The predicted increase in resistance in headseas compared with that in calm water is shown in Figure 15, for speeds of 30 and 40 knots. In this case JONSWAP wave spectra have been specified with wave heights as indicated. The wave periods selected are typical of North Sea conditions. For simplicity, zero wind speed has been assumed, although the windage drag is calculated.

It will be seen that the resistance increment in 2 m headseas amounts to about 50% of that in calm water, and in 3 m seas the increment is just over double. The predicted effect of a 30 knot headwind on this resistance would be to increase it by about 5%.

7.8 Effect of Modal Wave Period

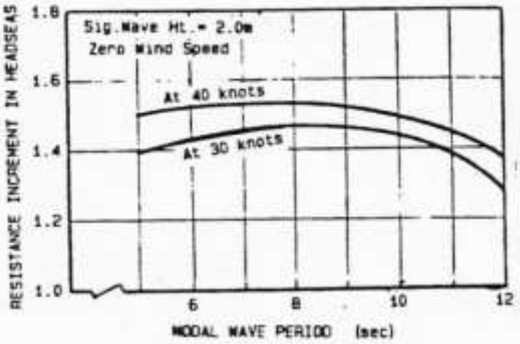

FIGURE 16: SES-600 RESISTANCE VARIATION WITH MODAL WAVE PERIOD

Figure 16 illustrates the predicted effect of change in modal (or peak) wave period in the 2 m headsea condition. As can be seen the maximum increase occurs in a wave period of about 8 s., where the craft is operating at a wave encounter frequency close to the natural pitching frequency (ie. at about 0.28 Hz). As the wave period and hence wave length is increased, the resistance gradually reduces and in swell type conditions with about twice the wave length, a reduction of nearly 15% is predicted to occur at a speed of 30 knots.

8. CONCLUSIONS

- Following a detailed study of SES calm water and overwave resistance measurements, prediction techniques have been developed which have been validated against model and full-scale trials data, for a number of different craft designs.

- The prediction methods have been incorporated into a computer program named 'SESDRAG'. This is able to predict resistance variations due to changes in hullform, lift setting, weight and wave height, including differences in wave spectra. The program covers full-hover, partial cushion and boating modes of operation, and establishes the balance in cushion and hull buoyancy loading for each case.

- The overwave resistance is based on the development of Resistance Increment Operators (RIO's), derived from the sidehull and cushion geometry, which when applied to wave encounter spectra can be used to predict the drag in irregular headseas. This approach has been well established in the analysis of model tests on monohulls, but this is believed to be the first occasion it has been applied to the prediction of SES resistance.

- An example of the use of SESDRAG has been given, which illustrates how the program can be used to predict the individual resistance components, the effect of weight and buoyant fraction changes, low speed performance both cushion-borne and boating, and the overwave headsea drag including the effect of change in modal wave period.

9. FUTURE WORK

SESDRAG is regarded as being in a state of continuing development, particularly with regard to the prediction of overwave resistance. Further correlation with both model and full-scale data is planned.

FIGURE 17. SES-700 MANNED MODEL "MOSES"

MTG Marinetechnik has recently designed a 10 m long manned model of SES-700, called MOSES - see Figure 17. This has now been built and will be tested by the German Navy Ship Test Centre in Eckernförde, near Kiel. This model will be operated in the open sea and thrust data will be obtained on all relative sea headings, over a wide range of speeds and sea states. It is planned to analyse this data to further validate SESDRAG, and to extend the program to cover the prediction of resistance on all headings.

10. ACKNOWLEDGMENT

The authors wish to thank MTG Marinetechnik and the German MoD, for permission to publish the results of this investigation.

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