CONCEPTUAL DESIGN METHODOLOGIES FOR FLYINGBOATS AND FLOATPLANES

S H Chicken
Cranfield University
Bedfordshire, UK

ABSTRACT

There are very few reliable guides to the conceptual design of modern flyingboats and floatplanes. The design tools available in the open press are extremely generalistic, often contradictory or were developed in the 1930s, 40s and 50s. Using extensive flyingboat, float and floatplane databases the author's studies have identified parametric patterns which will enable designers to confidently produce the initial design iterations for this these types of aircraft. In particular, this paper presents methodologies to design the initial dimensioned layout for any floatplane, along with the relevant performance modifications. Flyingboat configuration choice methods and mass estimation tools are also presented.

NOMENCLATURE

A	area (m^2)
AUM	all up mass (kg)
b	float or flyingboat beam (m)
C_{D0}	aerodynamic drag coefficient
h	float height (m)
l	length (m)
l_f	forebody length (m)
M	mass (kg)
s	float spacing (m)
$\dot{v}$	velocity (m/s)
z	spray height (m)
z_1	distance from float top to structure (m)
Δ	displacement (kg)
ρ	water density (kg/m^3)

INTRODUCTION

Confident appraisal of a variety of transport system options, ranging from long range, ultra-high volume freight to low utilisation pleasure, requires that adequate data be available for each option. Such data applicable to modern flyingboats and floatplanes is sparse and often contradictory. The author therefore decided to undertake a wide-ranging data and reference survey of flyingboat and floatplane designs and then develop a linked series of parametric design methodologies to enable the designer to produce a confident first iteration of such aircraft.

This paper represents a summary of the first 18 months of the studies towards a part-time PhD in Aerospace Vehicle Design at Cranfield University. In particular, the paper offers a complete set of validated tools to design the static aspects of a floatplane along with a partially complete performance estimation technique. Flyingboat configuration choice methods are also presented along with a mass estimation technique.

Definitions. Within the general definition of amphibious aircraft the following specific definitions are included.

A pure floatplane is defined as an aircraft which can only take off/land from/on water and derives its floatation from discrete floats.

An amphibious floatplane is defined as above but is equipped with wheels to enable it to take off/land from/on land in addition to water (see Figure 1).

A pure flyingboat is defined as an aircraft which can only take off/land from/on water and derives its floatation from a specially configured fuselage.

An amphibious flyingboat is defined as above but is equipped with wheels to enable it to take off/land from/on land in addition to water (see Figure 2).

Sources of Data. Specific aircraft data was used to compile a floatplane and flyingboat database. To ensure that a sufficiently large statistical sample was available for analysis the databases covered as much information as possible on monoplane flyingboats from 1936 to date and as many floatplanes as possible in the same period. This period was chosen as it represented the life of metal, semi-monocoque, monoplane aircraft. A total of 81 floatplanes and 130 flyingboats are included in the database to date. In addition to the aircraft database a float database was compiled from information gained from 10 current float manufacturers; 36 floats are included in this database. Research data such as NACA, ARC and MAEE (Marine Aircraft Experimental Establishment) reports were in many cases used as the start-point for developing more up-to-date design tools. Over 200 relevant reports have been examined to date. General data from books and articles was used to verify and/or weight the information derived from the specific aircraft database and the research data. Similarly, on-site visits to relevant sites with amphibious aircraft connections enabled first hand data to be gathered from actual aircraft and their designers and operators. Visits so far have included Dornier, Canadair, the Miami, Oslo and Vancouver seaplane bases, Forest Industries Flying Tankers and the Soesterberg, Pensacola, Hendon and Cosford aerospace museums.

Flyingboat Form. The form of a flyingboat is different from that of a land-based aircraft to reflect the design compromises enabling it to operate from water as well as the air (see Figure 3). In particular, the bottom of the fuselage is, ideally, flat to allow it to plane across the water surface on take-off and landing. To reduce the effect of water impact loads this planing bottom is usually set at a symmetric angle to the horizontal when viewed from the front elevation: the deadrise angle. There is usually a sharp discontinuity between the planing bottom and the rest of the fuselage. This is known as the chine and ensures that the water surface breaks cleanly away from the fuselage avoiding the Coanda effect holding the flyingboat to the water. Viewing the flyingboat from the side elevation illustrates the bow angle, necessary to help the flyingboat break through waves, and the step. The purpose of the step is, like the chines, to act as a discontinuity to the water flow during planing. This limits planing to the area forward of the step, around the centre of gravity, where the pitching moment changes are more controllable and stops the aft portion of the hull generating Coanda drag. The final point of note is that the flyingboat must be stable when at rest on the water. This is achieved by providing buoyancy away from the centreline in the form of tip floats, stubs or parts of the wing.

Float Form. The form of the floats used on floatplanes are similar to flyingboat hulls with some additional points of interest. The float sternpost angle must be at least equal to the take-off trim angle for the original landplane. If the angle is lower the stern of the float will trail in the water on take-off, significantly increasing take-off distance. The planing bottom of an inflatable float does not require deadrise to lessen the water-impact as it relies more upon the flexibility of the inflatable airbags to absorb the force (see Figure 4). The float main body must not only transfer the landing loads to the struts and thence to the main airframe structure, but must also displace the required volume of water. Internal frames can be either open or closed to form water-tight bulkheads which divide the float into the minimum of 4 approximately equal volume compartments required by FAR 23.751. The float structure should also be able to support the weight of passengers or maintenance staff moving on the upper surface. Stiffening the upper float surface can also provide extra flexibility of use by allowing a variety of strut fixing points and thus a variety of aircraft types' attachments. Although a well-rounded float top is aerodynamically sound and allows water to run off the float, a flat top and slab sides make passenger use safer and eases manufacture. Access to the inside of the float is required to check the structural integrity and to bail out any water leaks. The internal volume of the float can be used to transport fuel or cargo, although adequately sized and waterproof access doors are required. Main undercarriages are usually located behind the step in the less-heavily loaded afterbody. The hydrodynamics of the afterbody are also less important than that of the forebody, so discontinuities such as doors or semi-retractable wheels cause fewer problems. Nose undercarriages are frequently semi-retractable to allow the tyre to form a bow bumper. On pure floats a rubber bumper is often used for this purpose. Water rudders are attached to the rear of the float and must be able to be retracted when the floatplane is above a certain speed when taking-off and landing. Float support struts follow the same construction rules as similar wing support structures. However, a point to note is that any cross-float or spreader struts should be stressed to support the floatplane when used as lifting points for fork-lift trucks. Streamlined struts with an internal spar are commonly used in this role.

FLOATPLANES

In the vast majority of cases a floatplane will be created by the addition of floats to an existing landplane; only under exceptional circumstances will a floatplane be initially designed as such. This limits the design methodologies needed to a series of interrelated steps based on the known parameters of the landplane (see Figure 5). Dynamic stability and cost of ownership factors will be added later in the study.

Configuration Choice. The most common configuration for a floatplane is a twin float layout (see Figure 1), with the 2 floats not only providing buoyancy but also lateral stability. A less common configuration for post-World War 2 floatplanes has been a single float layout which relies on tip floats for stability (see Figure 6). In certain scenarios a single float configuration may be more cost-effective than a twin.

Twin Float System Mass. FAR 23.751 requires that the 2 floats of a twin-float floatplane provide 180% fresh water buoyancy. Using the float database the maximum aircraft AUM was calculated by taking the single float displacement, multiplying this by 2 to reflect the twin-float configuration and then dividing this by 1.8. Assuming that this proviso also applies to the lighter *experimental* category of aircraft an approximately linear relationship between floatplane AUM and additional float mass can be derived (see Figure 7) as follows:

$$M_{floats} = 0.11\ AUM$$

High AUM Floatplanes. Whilst the use of the float database technique was able to confidently estimate float masses for aircraft up to approximately 5000 kg it would be naive to carry the estimation much above this figure. A method was therefore required to estimate float mass data beyond this point. The floatplane database was examined and data on the 4 floatplanes of AUM above 5000 kg and sufficient additional data (empty mass) extracted. Cranfield University methods were used to estimate the mass of the undercarriage of the landplane based on the AUM. This estimate was then subtracted from the AUM to gain the mass of the undercarriage-less aircraft. This mass was then in turn subtracted from the mass of the floatplane to gain the float and strut mass. The results showed quite considerable deviation from the estimation technique detailed above. An attempt was made to validate the method using data for aircraft under 5000 kg AUM with known float mass. This too illustrated considerable scatter. However, these deviations were probably due to the assumptions inherent in the undercarriage mass estimation method; the known (as opposed to estimated) float mass of the Tupolev TB1, at 800kg, was close to the estimation technique results of 880kg. As all the estimated results produced conservative over-estimates it was decided that the relationship of float mass to AUM for aircraft below 5000 kg could be applied to heavier aircraft, but with care. Attempts to find mass data for large floatplanes would continue for the remaining time of the study.

Low AUM Floatplanes. Examining the data points for the floats fitted to the aircraft below an AUM of 1500 kg showed quite a significant amount of scatter from the linear estimation. In particular there was a significant difference between those floats fitted to FAR 23 aircraft and those registered as in the ultra-light /experimental /home-build category. When considering floats for these very light aircraft the float material has a large effect on mass (see Figure 8). Due to the scale of this discrepancy between material types a generalised float mass to AUM relationship is difficult to support. Therefore, for aircraft under 1500 kg a series of material-based relationships is proposed as follows:

$(M_{floats})_{metal} = 0.12\ AUM - 20$
$(M_{floats})_{composite} = 5 + 0.036\ AUM$
$(M_{floats})_{inflatable} = 5 + 0.057\ AUM$

Other Factors Affecting Float Mass. The large discrepancy between the relationships regarding those aircraft with AUM above and below 1500 kg indicated that factors other than aircraft AUM were involved. On examining the performance of the aircraft which were fitted with the lightweight floats it became clear that their landing speeds were significantly less than the more conventional aircraft. This factor has a great effect on the force acting on the floats and therefore their structural strength and mass. It was initially assumed that an energy-related $v^2_{landing}$ function was involved but this still did not group the lightweight and inflatable with the conventional floats. A single $v_{landing}$ term produced a slightly more acceptable data point grouping, as did the $AUM^{3/4}$ term derived from FAR 25.527. However, the scatter was such that no additional confidence could be placed in this method over the simple AUM relationships, and the pure float mass to AUM method is henceforward used alone.

Amphibious Floats. The above methods were then repeated for amphibious floats and the following equations deduced:

For AUM < 1500 kg: $M_{float} = 15 + 0.053\ AUM$
For AUM > 1500 kg: $M_{float} = 100 + 0.13\ AUM$

Single Float Configuration. Estimating the additional mass of single-float floatplanes was more problematical than that for twin-float aircraft as not only must any initial estimate include the tip floats but also all but 2 examples of single-float floatplanes in the database were military aircraft from the World War 2 period. These points add an element of doubt to the data not only due to age, but also due to the uncertainty as to how modern certifying authorities would view any extra displacement required of a single float. The FAA has been approached for guidance, but until an answer is received it is conservatively assumed that the single float would have to follow the 180% buoyancy rule of twin floats. An example of this not being applied is the Sea Thrush amphibious crop spraying aircraft which has an AUM when operating under the *restricted* category of 3859 kg (requiring a normal float displacement of 6946 kg) yet under this category can use 2 x Edo 4930 floats of 4476 kg displacement. A further complicating factor is that most single-float floatplanes were purpose designed rather than adaptations of conventional land-based aircraft. The following method was used to estimate the additional mass of a single float configuration. First, an assumed aircraft AUM was multiplied by 1.8 to reflect the 180% buoyancy requirement. Next, a graph of existing float displacement to mass was produced using the modern float database. The relationship between these 2 variables was estimated as 0.062 AUM. Therefore the mass of a single float could be derived from this. The additional mass of the tip floats was estimated using the technique described in the flyingboat section of this paper. The resulting relationship is:

$(M_{float})_{single} = 0.176\ AUM$

Float Length. Inspection of the float database revealed a dog-legged linear relationship between floatplane AUM and float length (see Figure 9). Thus 2 equations are proposed as follows:

For AUM < 2500 kg: $l_{float} = 3.5 + 0.0013$ AUM
For AUM > 2500 kg: $l_{float} = 7.5 + 0.00036$ AUM

As already discussed under float mass there are only 2 data points for civilian single float floatplanes, one of which had no AUM data. It was therefore decided to check the relationship between the float length of military twin and single float floatplanes and assume the same relationship held for civilian twin to single float floatplanes. Thus from Figure 9 for military twin floats (AUM > 3500 kg):

$l_{float} = 6 + 0.00048$ AUM

and for military single float planes:

$l_{float} = 6 + 0.0074$ AUM

Therefore assume AUM factor for twin to single comparison is 1.5. When applied to the previous equations to model a projected civilian single floatplane the results are:

For AUM< 2500kg: $l_{float} = 3.5 + 0.00195$ AUM
For AUM > 2500kg: $l_{float} = 7.5 + 0.00054$ AUM

Float Beam. A number of variables were plotted against float beam but only float length presented a close relationship resulting in the following relationships:

Twin float length/beam ratio = 7.5
Single float length/beam ratio = 6.9

Float Height. A number of variables were plotted against float height but only float length and beam presented a close relationship. Note that the inflatable floats gave uniformly high l/h and b/h ratios and inspection of these floats reveals lower than normal heights for all such floats due to their inflatable bag construction. As float length is the first dimension to be derived from the primary floatplane AUM variable it was decided to use the l/b ratio in preference to that for b/h. The inflatable float data was removed resulting in the relationship:

Float length/height ratio = 8.75

Float Forebody Length. As expected, the closest relationships with forebody length was that with total length as follows:

Twin float length/forebody length = 2.0
Single float length/forebody length= 1.8

Spray Height. The distance of the floatplane fuselage or propeller above the waterline can be dependent on spray height. This subject has been studied in depth with regard to flyingboats but no information could be found regarding floatplanes. Therefore, a simple statistical method based on the database was derived. The vertical height from the top of the float to the nearest piece of major structure (eg fuselage/wing) was plotted from the available data. The data was plotted against AUM and, as could be expected, the statistical scatter was considerable as many other floatplane configuration factors influence the position of the float relative to the nearest structure. Scatter was also present when the data was plotted against aircraft span in an attempt to add a configuration-related factor. The data was then separated into 3 categories of single engine-twin float, single engine-single float and multi-engine-twin float to examine configuration effects. None gave results from which a relationship could be confidently developed, yet the scatter was less than when no configuration breakdown was included. Three very approximate relationships are therefore proposed.

Single engine-twin float: $z_1 = 0.54 + 1.2\times10^{-4}$ AUM
Single engine-single float: $z_1 = 0.35 + 2\times10^{-4}$ AUM
Multi-engine-twin float: $z_1 = 0.9 + 4.4\times10^{-5}$ AUM

Note that factors not included above, such as propeller to float clearance and fuselage (as opposed to wing) mounting for multi-engine floatplanes has a large effect on float to structure distance.

Static Stability. Static stability of floatplanes can be accurately calculated once the exact form of the floats is known[1,2]. However, until then approximate methods are required. Based on classic metacentric equations[3], methods were developed for longitudinal stability, resulting in a maximum safe centre of gravity to centre of buoyancy height, and for lateral stability, resulting in a minimum safe float spacing.

For single float floatplanes:

$$h_{max} = \frac{85.4b(0.91)^3}{AUM} - 0.59\left[\frac{AUM}{0.454}\right]^{1/3}$$

For twin float floatplanes:

$$h_{max} = \frac{170.8b(0.91)^3}{AUM} - 0.6\left[\frac{AUM}{0.454}\right]^{1/3}$$

$$s_{min} = \left[\left(\frac{12AUM}{10251}\left[\sqrt{\left(\frac{AUM}{0.454}\right)} + h\right] - 2b^3\right)\frac{1}{6b}\right]^{1/2}$$

Purchase Price. To aid designers in costing newly designed floats existing float costs were also estimated as a function of displacement. Note all costs are in 1994 \$US. In a similar manner to float mass, the cost relationship changed significantly between lightweight and more conventional construction. For $\Delta > 1500$ kg a linear relationship was defined as follows:

cost = $15\Delta - 5000$

In the lightweight area the pattern of the float mass relationship reoccurs, but with the aluminium floats cost gradient being significantly greater than the equivalent inflatable or composite floats (see Figure 10). It is suspected that parts-count cost considerations are responsible for this effect. Unlike the float mass the difference in aluminium float gradient is such that relationships are postulated for material types within the lightweight ($\Delta < 1500$ kg) float category as follows:
Metal floats: cost = $8\Delta - 500$
Composite/Inflatable floats: cost = $500 + 2\Delta$

For amphibious floats ($\Delta < 1500$ kg) the relationship is:

cost = $25.5\Delta - 13000$
For lightweight amphibious floats the metal, inflatable and composite constructions are significantly closer together than pure floats (although still in the same ranking) and therefore the relationship for amphibious floats with displacement less than 1500 kg is:

cost = $800 + 4.2\Delta$

Float Kits. Many of the smaller displacement floats can be purchased in kit format at reduced price, averaging 53% for pure floats and 70% for amphibians. Note that the fibreglass and the metal floats give similar kit-to-assembled cost ratios.

Changes in Performance. Having established the physical dimensions and installation details of floats on an existing aircraft there was the need to develop a method of predicting the changes in performance due to those floats. The major changes in performance are range, rate of climb and speed. The prime factor of a float installation which affects these aspects is C_{D_0}. This assumes that the AUM of the land and floatplane remain equal and that lift (and therefore lift-induced drag) due to the float form is negligible. The additional parasite drag of a float installation is caused by a combination of the floats themselves and the supporting struts. Hoerner[4] provides some float drag data and estimates that a normal (as opposed to heavily streamlined) float has a C_{D_0} of 0.22 based on the float cross-sectional area. Thurston[5] provides an estimate of 0.2 based, again, on cross-sectional area. As float height and beam are known dimensions an approximation of cross-sectional area is available. Hoerner also includes data on the drag of undercarriage (uc) struts, a good approximation of float struts. These figures were used to compare estimated and actual floatplane C_{D_0} values and in particular the effect on range. Considering the Breguet range equation, expressing the range of a floatplane over the range of the equivalent landplane and assuming that W_0/W_1 is constant in both cases:

$$range\ ratio = \frac{range_{floatplane}}{range_{landplane}} = \frac{C_{D0\ landplane}}{C_{D0\ floatplan}}$$

Using the above method and C_{D0} values from Smith[6] range ratios were calculated for 9 floatplanes based on fixed uc landplanes and 2 with retractable uc. The average ratio for fixed uc landplanes was 0.89; that for retractable uc aircraft was 0.78. The floatplane database was examined and landplane and equivalent floatplane performance figures extracted. The average range ratio for fixed and retractable uc aircraft was 0.90 and 0.75 respectively. This is sufficiently close to the calculated figures to confidently use the average ratio method for estimating floatplane performance based on known landplane data. However, the small data sample for retractable uc aircraft indicates that this method should only be used with care in that area. Thus the average change in performance is summarised as:

Floatplane (fixed uc) speed reduction = 0.91
Floatplane (retract uc) speed reduction = 0.74
Floatplane (fixed uc) rate of climb reduction = 0.84
Floatplane (retract uc) rate of climb reduction = 0.72
Floatplane (fixed uc) range reduction = 0.90
Floatplane (retract uc) range reduction = 0.75

Weathercock Stability. Many floatplanes use additional ventral, dorsal or tailplane-mounted fins to add area to the rear of the aircraft. This is to off-set the greater side area of the part of the floats forward of the aerodynamic centre compared to the side area aft. 51% of the aircraft in the floatplane database had such methods with ventral fins being the most popular (37%).

Float Customer Requirements. Amphibious and pure floatplane users were asked to detail their desirable requirements in addition to the mandatory buoyancy and ever-present cost/performance points. The following list is a summary of their views with design-related notes in parenthesis.

1. High Impact Resistance of Float Bottom.
- position and number of internal or external longitudinal and lateral stiffeners (cost of manufacture, mass, hydroboosters, skegs, watertight bulkheads).
- choice of materials and skin thickness (aluminium, inflatable or composites, cost of manufacture and mass).
- deadrise (displacement/draft effects and landing force resolution).

2. Maintainability of Floats.
- internal access (bilge pumps and repair access).
- choice of materials (repair following damage and cost).
- joints (bonded or rivetted for cost of manufacture and leak sealing processes).
- access to strut joints and rudder mechanism for preventative maintenance (aerodynamic effects).

3. Passenger Safety.
- high rearwards buoyancy and flat top enables passengers and maintainers to move along rear of float safely (performance effects).

4. Constructive use of Float Internal Volume.
- access panel size and water tightness of volumes used for baggage or fuel (cost of manufacture, loading of cut-outs).

5. Water Performance.
- conflicting requirement of rapid take-off (ie 'slippery' float) and rapid deceleration (for aircraft without variable pitch propellers).

FLYINGBOATS

The database was first consulted to confirm that there was an ongoing requirement to design flyingboats. The data clearly illustrated the rise of the type in the 1930s and the precipitous fall following World War 2 (see Figure 11). However, the data also showed a continuing, steady output of 1 to 2 new flyingboat designs per type per year. Although this pattern has been somewhat exaggerated in the recent past due to the break-up of the monolithic Warsaw Pact aerospace industry into competing design teams, the data illustrated an ongoing need for flyingboat design tools. Many methods already exist to aid the conceptual design of conventional aircraft. This part of the study investigates the additional tools required to enable a modern flyingboat conceptual design to be completed. Like so many design activities flyingboat conceptual design is a cycle. In the particular case of flyingboats the initial design cycle involves mass, configuration, static and dynamic stability, buoyancy and spray height. This cycle is represented diagrammatically in Figure 12; note that the dotted boxes represent subjects which, along with cost of ownership, will be covered later in the study.

General Configuration. To aid in the generalisation of data a number of AUM and role classifications were created:

AUM < 1000 kg	= Ultra-light (UL)
1000 < AUM < 2000	= Light (L)
2000 < AUM < 8000	= Light-medium (LM)
8000 < AUM < 15000	= Medium (M)
15000 < AUM < 36000	= Heavy (H)
36000 < AUM	= Super Heavy (SH)

Transport of Mass (T(M)) - a flyingboat designed to transport high mass/low volume payloads such as military non-cargo loads or fire extinguishing foams.

Transport of Volume (T(V)) - a flying boat designed to transport high volume/low mass payloads such as cargo or passengers.

Transport of Volume/Mass developed from Transport of Mass/Volume (T(V) or(M)D T(M)or(V)) - a flyingboat used for the transport of either mass or volume loads but developed directly from one designed for the other role.

Utility (U) - a flyingboat designed for multi-purpose use by small operators from austere locations.

Private (P) - a flyingboat designed for recreational use.

Configuration Choice. To form the basis of conceptual design iterations it is essential that the designer has an early indication of the configuration of the flyingboat. The most important factor which influences this is the maintenance of distance between the propulsion source (propeller or jet) and the water spray generated at take-off and landing. The aircraft database was studied and 8 basic flyingboat configurations were distilled from the details available. These are presented diagrammatically in Figure 13. The high wing - high engine configuration was only frequently used in the late 1930s and it was assumed that the prime reason for using this over the purely high wing solution was the ease of changing engine types, as this was a period of very rapid engine development. Thus data relating to this configuration was added to the pure high wing data. Having decided on the configuration options the database was then studied to see if any patterns were present . It was noted that 75% of SH flyingboats were T(V) or T(M)DT(V), thus generating the requirement for voluminous and therefore high fuselages. It is not therefore surprising that design synergy leads 95% of this type of flying boat to use the fuselage height to mount the wings and engines well above the spray. When H-type flyingboats were examined the data was split one of 2 ways. If the role was T(V) or T(M)DT(V) all but one were high winged, following the logic of the SH type. However, where there was no original high volume requirement there was a fairly even spread of configurations, the requirement for the low (air) whetted area of a smaller fuselage outweighing the advantages of larger useable volume. M and LM type flyingboats do not have roles requiring large volumes but the designers clearly had the height of a standing man in mind when designing the fuselage. Thus high and parasol wing solutions are still popular. For L and UL flyingboats safety is paramount due to their utility roles and large amateur, private operator numbers. Thus keeping the propeller away from the pilot/passenger has equal, if not greater, importance to spray height. Thus HE-P and HE-CO-P solutions are very popular. Overall the following guidance can be gained from this exercise.

SH = HW   H + T(V) = HW
H + T(M) = HW or PW or GW
M = Any solution

LM = HW or HE-CO-P or HE-P
L = HE-P or HE-T or HE-CO-P
UL = HE-P or HE-CO-P

Lateral Stability Method Choice. The database was examined for patterns of lateral static stabilising method configuration, form and location. The vast majority of flyingboats used floats of some form to gain lateral stability; only 13% used sponsons and 5% the wing volume. Of the flyingboats which used floats 15% had some method of retracting the floats to reduce drag. A significant minority (40% of data sample) used some form of design synergy in mounting their floats, for example an aileron attachment frame location. It is likely that more used synergy, but the method was not visible on the photographs or drawings in the database. Ten generalised float forms were identified from the database, of which stepped and unstepped teardrop-shapes, at 41% and 27% of the sample, were the most popular. There seemed to be no apparent reason why some floats were stepped and others were not. However, it was noted that for the majority of in-life updates (eg PBY-5 to PBN) unstepped floats were replaced by stepped. Further work is required to identify the specific advantages and disadvantages of various float and strut configurations, particularly in relation to any additional wing structure mass. The most popular position for stabilising floats (31% of data sample) was at 66-70% semi-span, with 67% of the data sample lying between 66% and 80% semi-span.

Planing Bottom Area. It is essential that the planing bottom generates sufficient hydrodynamic lift to ensure that the flyingboat planes successfully. The database was examined to determine if an empirical method could be derived to check this. Intuitively, planing bottom lift should be some function of forebody area, take-off speed squared, all-up mass and deadrise. As changes in deadrise angles across the database were small this factor was initially deemed negligible. When forebody area was examined across the database in order of AUM a relatively linear pattern emerged. The linearity was also apparent when forebody area was plotted directly against AUM. Other factors, including an attempt to define a planing bottom lift coefficient did not achieve any acceptable relationships. Thus a simplistic AUM to area relationship is postulated:

for SH and H: $A = 10 + 5.8\times10^{-4}$ AUM
for M, LM, L and UL: $A = 1.4 + 1.5\times10^{-3}$ AUM

Forebody Length-beam Ratio. Conventional practice as described in many references states that flyingboat's forebody length-beam ratio - the structural configuration factor which most effects planing performance - should be approximately 4. This was borne out by the database. For the time period of the study the ratio oscillated between 2.2 and 6.8 with 3.5 being the average.

Tail Configuration. Flyingboat tails have 3 additional design requirements to those of landplanes. Firstly, the horizontal surfaces must be sufficiently high to avoid the impact of spray. Secondly, as the water-borne flyingboat has no rigid runway to react conventional undercarriage nosewheel steering or differential braking loads, steering at low airspeeds for centreline thrust aircraft must be completed using a combination of water and air rudders, the latter therefore having potentially greater importance than that of a landplane. Finally, the common flyingboat high engine position, with its related large thrust moment arm, puts greater emphasis on the horizontal tail than similarly sized landplanes. The data for flyingboat tails was extracted from the database. To provide a comparison, a similar number of landplane tail details was extracted from Janes using approximately the same number of types of landplanes per 5 year date bracket as was gained for flyingboats from the database. As expected the results showed the flyingboat designers' preference for high and mid-mounted horizontal tailplanes. Additionally, there were more twin and triple vertical tails on flyingboats. It is assumed that this method was used to ensure that the rudders were placed into the propeller slipstream to generate greater directional force at low taxiing speeds.

Tail Volume Coefficients. The vertical and horizontal tail volume coefficients were examined for a variety of land-based aircraft and flyingboats. The data was split into four engine position related sets to account for one of the main factors affecting the vertical variable: 4 or more engined, twin engined, fuselage mounted multi-engined and single engined. It was initially assumed that flyingboats, with their high forward fuselage sides and high engine positions, would have significantly greater fin and horizontal tail volume coefficients than similarly configured landplanes. However, this was not the case in all but the single engined aircraft. For multi-engined wing and fuselage mounted engined land-based aircraft the average coefficients were 5-8% above that of similar flyingboats. This was even the case when aircraft with similar engine-out power cases and vertical engine positions were examined along with other influencing factors such as T-tails and low landing speeds. However, as the percentage difference is within the 10% error envelope expected of the dimension estimation method it was decided that no difference between land-based and flyingboat vertical tail coefficients be postulated for these classes of aircraft. The single engined flyingboat class showed a 19% increase in both vertical and horizontal tail volume coefficients over a similar group of land-based aircraft. These differences are outside the method error envelope and are therefore considered to be significant. Note this effect includes the fact that all of the flyingboats have mid or T tails and put the fin in the propeller slipstream, further increasing its effectiveness.

Mass Estimation. The aim of the mass estimation technique is to provide a valid approximation of the extra mass of a flyingboat over that of a similar conventional aircraft. Thus existing, well proven, mass estimation techniques for conventional aircraft can be used to gain the first estimate of the flyingboat mass and the additional masses can then be added. Stinton[7] gives an overall approximation of the extra mass of the structure of a pure flyingboat as 5% over the equivalent landplane structural mass, rising to 10% for an amphibious flying boat. However, common sense suggests that there should be a scale factor between the extra mass required for a small flyingboat to that for a very large one. Thus it was decided to divide the extra mass into 3 major independent areas, the planing bottom, the chosen form of lateral stability and the extra equipment required to operate a flyingboat.

Planing Bottom Mass Estimation. Burt[8] provides a graph from which planing bottom mass can be deduced from the AUM. However, as the source data of the graph is not explained it was decided to develop a planing bottom mass estimation technique based on information obtained from existing flyingboats. First the mass of a conventional aircraft fuselage having the same dimensions as the flyingboat was estimated using Cranfield University methods. The proportion of the area of the fuselage which equated to the area of the flyingboat's planing bottom was then calculated. Next the mass of the planing bottom of actual flyingboats was calculated and the difference between the actual and theoretical figures examined. The actual mass was gained either from visiting examples of the relevant aircraft and taking detailed measurements of the structure, using data from the aircraft's structural repair manual or other sources of data such as detailed drawings from magazines. In some cases assumptions had to be made to fill in gaps in the latter sources, but if this was the case similar authoritative data was used from the aircraft closest in size. As expected the conventional fuselage estimation technique significantly underestimated the planing bottom mass. This overestimate ranged from over 200% in the case of the lighter flyingboats to 15% for the very large Shetland. It was concluded that AUM was a significant variable and both the error between the estimate of the actual masses and the actual mass itself were plotted as a percentage of AUM against AUM. The latter relationship produced the closest statistical pattern (see Figure 14) and the resultant assumed line is recommended as an estimation method. The method was validated by applying the Shin Meiwa US1 details to the method which resulted in an estimated planing bottom mass of 1.3% AUM which is 512 kg. The actual mass is 565.5 kg, an acceptable error of 6%. Note that in all cases Burt's graphical method significantly overestimated the planing bottom mass. The breakdown of the structural mass into skin, frame and stringer masses was also examined. The only pattern readily visible was that the lighter flyingboats tended to have a higher skin mass than the estimated. This is probably due to the need to countersink bottom fasteners resulting in a thicker skin than theoretically necessary with consequently less stiffness being required from stringers and frames.

Extra Equipment Mass. Several contemporary and historic references were used to identify the main items of extra equipment required by amphibious aircraft over more conventional aircraft. The main item from the mass point of view was the anchor. Anchors are required to withstand the force applied to the flyingboat or floatplane from both wind and current/tide. Thus the size and therefore mass of an anchor is related to both the air and water-related drag and to the situation the aircraft is expected to be anchored in. Developing concepts outlined in MAEE papers[9,10]:

$$(M_{anchor})_{tide} = 2.2\times10^{-6}\ AUM\ v^3_{tide}$$
$$(M_{anchor})_{wind} = 0.024\ C_{DO}\ v^2_{wind}\ S$$
$$(M_{anchor})_{wind} = 7.4\times10^{-4}\ v^2_{wind} S \quad (\text{ if } C_{DO} \text{ unknown})$$

Tip Float Mass. Initially, the mass of tip floats was estimated using a structural breakdown technique similar to that used for the planing bottom. However, when validation examples were compared to the results an unacceptably large scatter was evident. This was probably because small errors in assumptions and measurements had a proportionately larger effect on the relatively small floats compared to the large planing bottom. It was therefore decided to only use actual float masses. The masses are presented as a % of AUM in Figure 15. Note that the Princess is the only data point with retractable floats. It is planned to continue to add to this information throughout the term of the study as 6 data points is clearly not a valid statistical sample. A method of estimating the additional wing mass necessary to support tip float loads was developed but again failed when validation examples were applied.

Stub Mass. The second most popular method of gaining on-water lateral static stability is thick, low aspect ratio, wing-like structures attached to the hull near the waterline and known as stubs (see Figure 2). Alternative names are stümmel, sponsons or sea-wings. Although stubs have a higher mass and air drag for the same lateral restoring moment than tip floats they can suppress spray, have potential usable volume near the aircraft c of g, can ease embarkation and are considerably more robust than tip floats. However, the main perceived disadvantage of stubs is their high mass in comparison with tip floats and therefore this particular aspect was investigated in more detail. The only reference found where actual stub mass was available (as opposed to a generalised theoretical percentage) was a 1928 Dornier paper[11]. The extremely high percentage of AUM, combined with the date of the reference cast doubts on the validity of the data, and therefore the related information on other Dornier structures was examined. Component mass estimation using Cranfield University methods were, on average, 51% of the masses quoted in the Dornier reference. This factor was therefore applied to the Dornier stub masses (see Figure 16). This graph can be used to estimate stub masses on modern aluminium alloy structures.

CONCLUDING REMARKS

The author's studies have identified validated parametric relationships for the overall dimensions, additional mass and performance effects of converting a landplane to a floatplane. Confident lateral and longitudinal stability limits are also identified along with initial purchase price relationships. This quantitative work is augmented by a list of qualitative customer requirements. Similar parametric processes have been developed to enable flyingboat designers to choose the optimum configuration and estimate the additional mass of their design over that of a similarly configured landplane. These design methodologies will form the basis of further work on hydrodynamic and aerodynamic performance and cost of ownership for flyingboats and floatplanes, the end result being a comprehensive and authoritative series of amphibious aircraft design tools.

ACKNOWLEDGEMENTS

The author gratefully acknowledges the help and encouragement of the amphibious aircraft industry without whose open provision of information this study would not have been possible. In particular, thanks to the engineers of Canadair, Dornier, Lake, Edo, Full Lotus, Wipaire, Aerocomp, Forest Industries Flying Tankers, Shin Meiwa, the operators at Oslo, Vancouver and Miami seaplane bases and the curators of the museums at Soesterberg, Pensacola, Cosford and Hendon.

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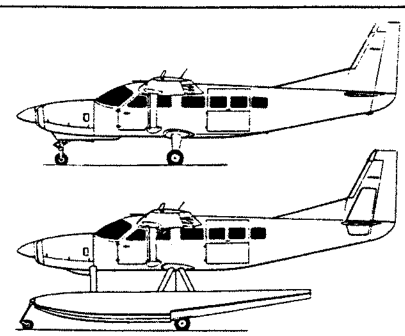

Figure 1. Cessna Caravan Amphibious Floatplane.

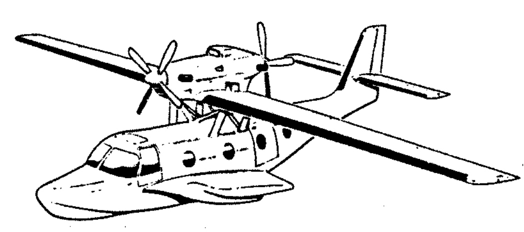

Figure 2. Dornier Seastar Amphibious Flyingboat.

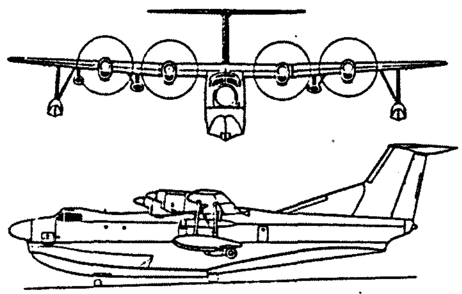

Figure 3. Shin Meiwa PS1 Flyingboat.

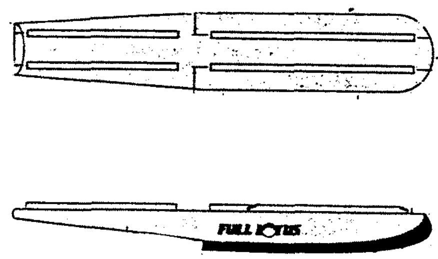

Figure 4. Full Lotus Inflatable Floats.

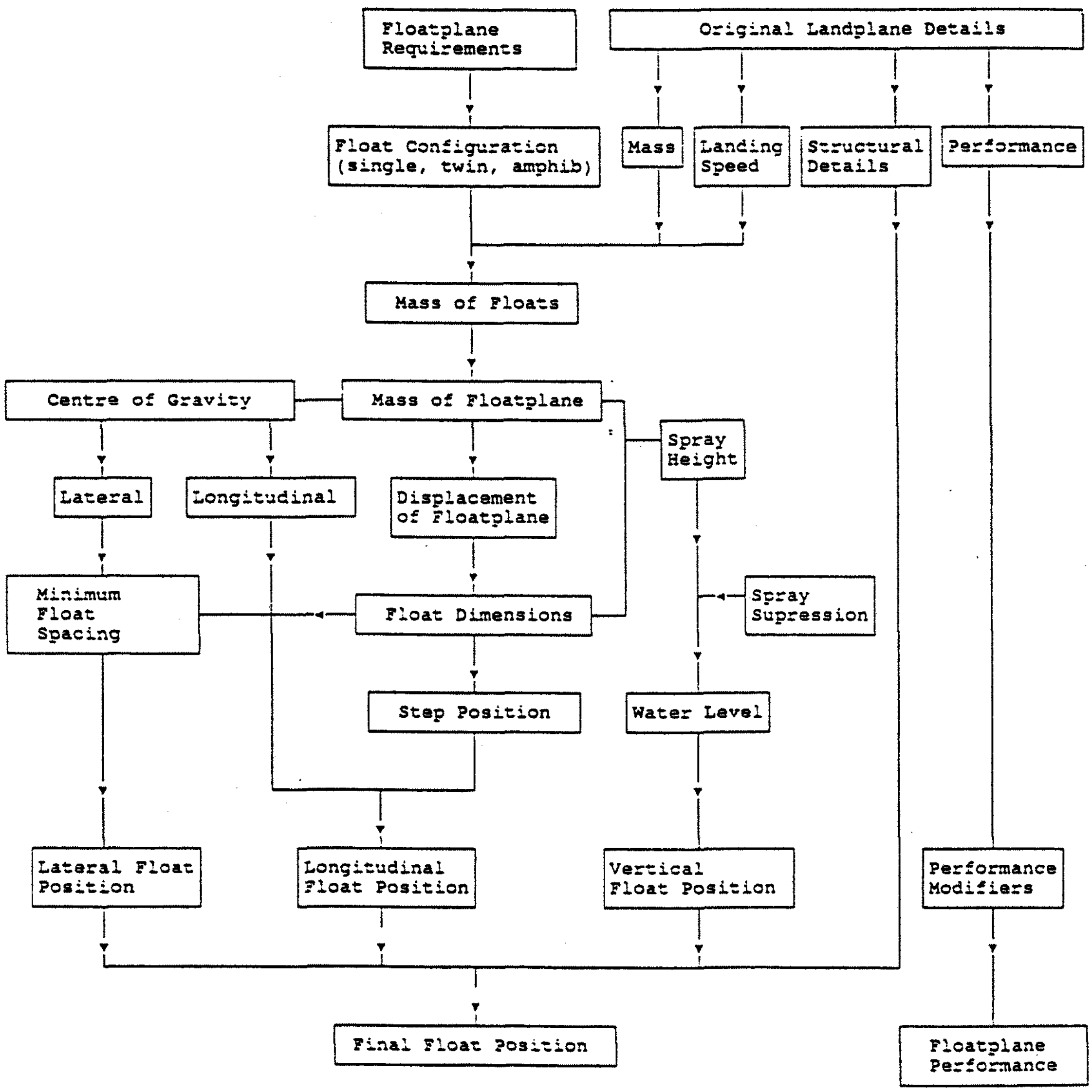

Figure 5. Floatplane Design Methodology.

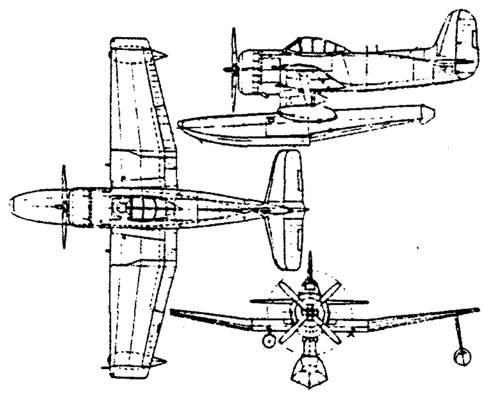

Figure 6. Curtiss SC-1 Single Float Floatplane.

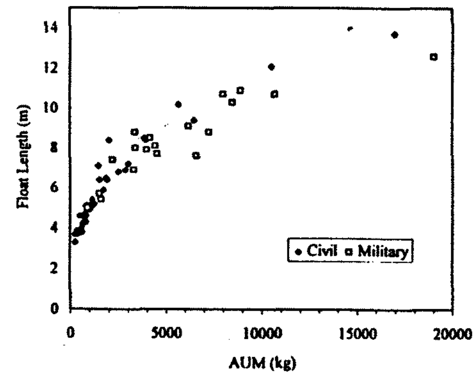

Figure 9. Float Length Graph.

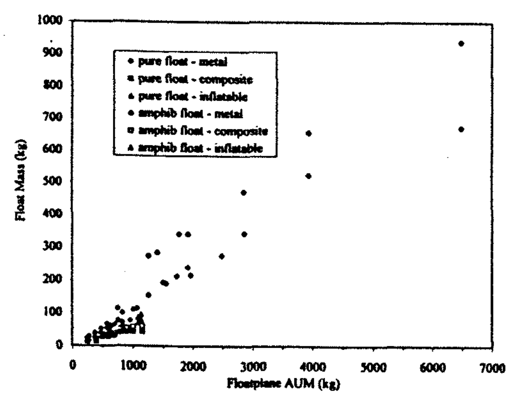

Figure 7. Float Mass Graph.

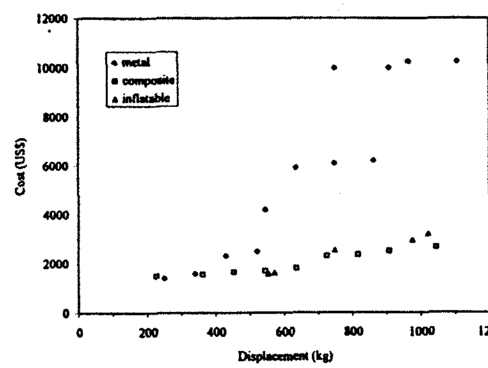

Figure 10. Float Cost Graph.

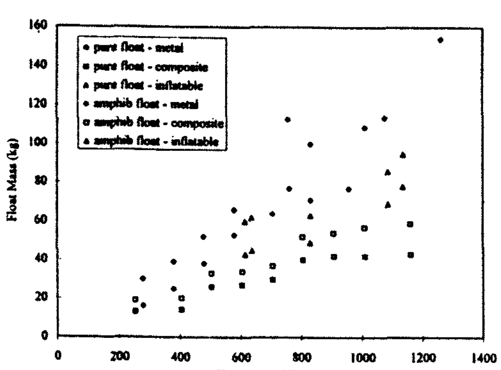

Figure 8. Float Mass Graph (Light Aircraft).

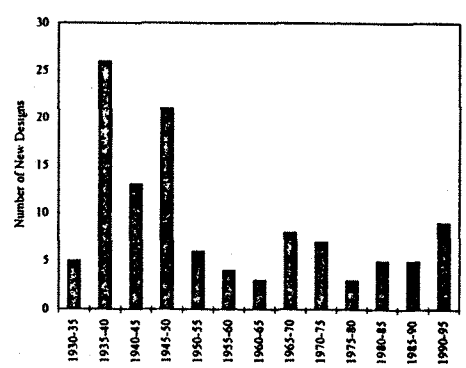

Figure 11. Flyingboat Chronology.

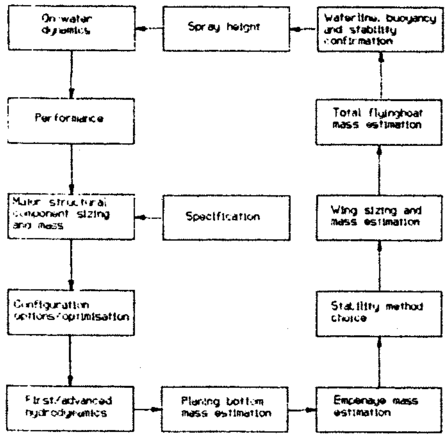

Figure 12. Flyingboat Design Methodology.

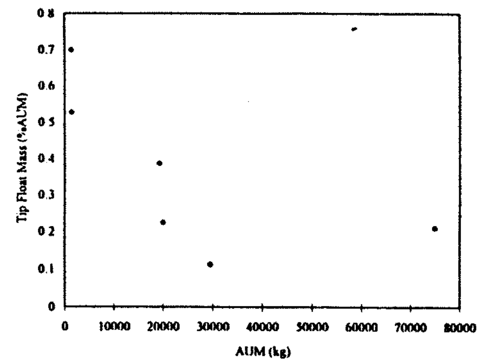

Figure 15. Tip Float Mass Graph.

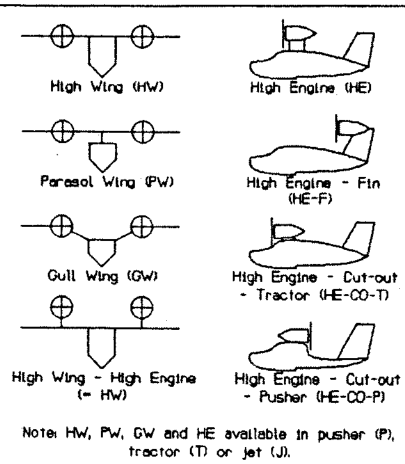

Figure 13. Flyingboat Configurations.

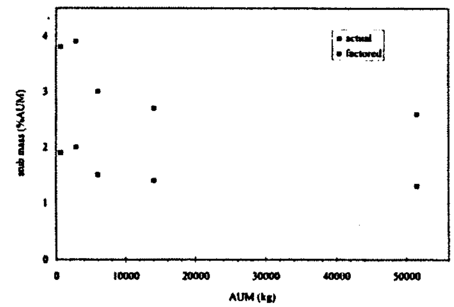

Figure 16. Stub Mass Graph.

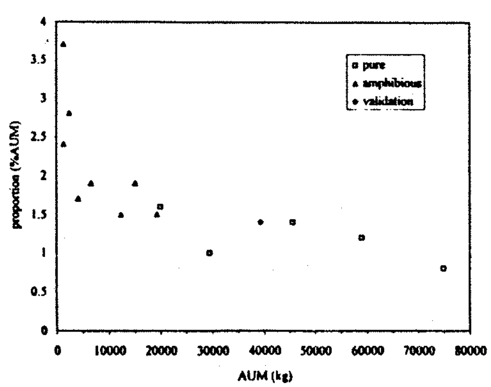

Figure 14. Planing Botton Mass Graph.