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HELICOPTER DESIGN SYNTHESIS

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Abstract

This paper describes the efforts carried out at Southampton University, U.K., to develop a computer program in the aid of preliminary helicopter design synthesis. The work concerns itself with the aerodynamic and dynamic aspects of the design of helicopters of the conventional configuration. The basic philosophy behind the development of such a program is to provide the researcher with a tool which will allow him to readily assess the multi-variable relationships between the various input design requirements in the earliest stages of project definition.

This report includes a brief discussion about the limitations and capabilities of the program as well as some of the outputs obtainable from typical program runs.

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1. Introduction

Only recently have digital computers been used to aid helicopter design. Most efforts, however, seem to have been directed towards the structural and aeroelastic design analysis. For aerodynamic performance analysis, the detailed rotor performance prediction with its associated complex near-field flow and wake modelling has received the most attention. The possibility of applying the digital computer to the base-line design feasibility stage appears to have been overlooked.

A helicopter design synthesis program[1,2], called HELISOTON, is being developed at Southampton University. The emphasis of this work is to produce a time-efficient computer program capable of performing the preliminary design analysis of the aerodynamic and dynamic characteristics of a projected base-line helicopter (H/C) of the conventional lay-out and to assess the effect of the chosen input parameters on those characteristics. The program has a limited decision making capability.

Time-efficiency dictates that lengthy detailed methods of analysis must be avoided and that approximate methods of computation have to be adopted. Semi-empirical statistical relationships are used in the estimation of, for instance, the empty weight breakdown; the blade element theory (BET) approach is employed in the analysis of the rotor aerodynamics (A/D) and installed power; simple mass distribution models are adopted to determine the shape of the H/C as well as its centre of gravity (cg) position and the second moments of inertia about the three axes; the linearised, uncoupled equations of motion are chosen to perform the trim, static stability, dynamic stability and response calculations. These are the main underlying assumptions upon which the simplicity and the weaknesses of the program depend.

The general philosophy of the program could be applied to H/C of alternative configurations. The conventional layout was chosen, however, on the basis of being the best-documented one and, for which a large design experience exists. Arguments about the intrinsic merits of the conventional H/C can be found in several references[3,4]. Furthermore, the conventional H/C covers a range of size and diversity of roles unrivalled by rotorcraft of any other layout both in civil and in military spheres. A practical and most emphatic argument in favour of the capabilities of the conventional H/C has recently been given by the Russian MI-26 helicopter.

2. Program Description

2.1 General

HELISOTON is a digital computer program of modular construction written in extended ICL 2900 FORTRAN. Modular construction makes the task of updating and developing the program easier.

2.2 Operation and Functions

HELISOTON was developed primarily to provide a simple and fast automated prediction of a helicopter's AUW, installed power and size as a function of the aircraft role, specification and mission profile. The program, when used in this mode, can be run for different sets of input parameters in order to perform sensitivity analyses. This monitoring function is performed by the iteration procedure outlined in Fig.3.

The same basic iteration was later linked to a series of outer iterative loops (Fig.4) so that the program could carry out simple optimisation decisions related to the preliminary stages of design. The program, when in this mode, can be used to simply select design parameters, ruling out those solutions that could not be expected to lead to efficient or practical final base-line designs.

In either mode, HELISOTON can be used for data generation in conjunction with external optimisation programs covering fields wider than aerodynamics and dynamics and/or using more detailed, time-consuming computation models. Facilities also exist to allow for one engine out hover capability, the transport of underslung off-centre loads and the installation of engines of specified s.f.c.

2.3 Running Times

HELISOTON has been run on ICL 2970, ICL 1906 and CDC 7600 computers with minimal changes, the FORTRAN used being very similar to standard ANSI-FORTRAN.

The program has a CPU time monitoring module. This has allowed CPU time estimates to be performed. The time taken for a single run depends on how many inner and outer iterations have been performed and the particular computer being used. The net CPU time for typical "monitor" runs ranges from 5s to 20s using the USCS high precision (virtual storage) ICL 2970 computer.

3. Main Operational Features

3.1 Basic Iteration Block

This block evaluates the H/C A.U.W. and installed power by iteration. It also checks that several design parameters do not exceed limits that would lead to nonsensical results.

3.1.1 A.U.W. and Pins

This basic block solves the following parametric equations:-

$$W_T = W_p + W_E + W_F \qquad \text{Eq.1}$$

$$W_E = \sum_{n=1}^{12} F_n \,(W_T,\ W_p,\ W_F,\ P_{ins},\ k_R,\ \text{etc}) \qquad \text{Eq.2}$$

$$W_F = W_F \,(P_{ins},\ k_{mp},\ W_F) \qquad \text{Eq.3}$$

$$P_{ins} = P_{ins} \,(W_T,\ x_{cg},\ k_E) \qquad \text{Eq.4}$$

$$x_{cg} = x_{cg} \,(W_T,\ k_{md}) \qquad \text{Eq.5}$$

where the 'k' parameters refer to input data conditions or specifications (see notation).

Convergence is accelerated by means of a 'damper' subroutine which uses the local rates of convergence of the all-up-weight W_T and the partial derivative of the installed power P_{ins} with respect to W_T.

The installed power is derived from the power required to hover, the requirement to achieve a target maximum speed or a maximum rate of climb depending on whether engine out is admissible in hover or not. In each case, appropriate factors are applied to the required powers to obtain equivalent 'zero-altitude' ISA installed powers, the greatest of which is then chosen.

3.1.2 Mass Distribution Models

The distribution of mass in a H/C is a function of its role and its overall shape. HELISOTON provides basic mass distribution models for conventional H/C designs corresponding to 5 roles: light utility; transport; search and rescue/A.S.W.; tactical strike; and sky-crane. For each case, a corresponding simple fuselage shape model is provided, (Fig.5).

The identifiable elements of mass considered in the distribution are: body group; payload; fuel-load; transmission system; engines; main and tail rotors; empennage; undercarriage and instrumentation.

From this distribution, the cg position and the second moments of inertia can be readily found.

$$\bar{X}_i = \left[\sum_{n=1}^{10} (X_{ni} W_n) \right] / W_T \qquad \text{Eq.6}$$

$$I_{ii} = \sum_{n=1}^{10} \left[I_{CG_{ii}} + W_n (X^2_{n(i+1)} + X^2_{n(i+2)} \right] \qquad \text{Eq.7}$$

3.1.3 Empty Weight

Predictions of the empty weight breakdown is achieved by means of statistical semi-empirical relationships. These statistical relationships take account of normal acceleration requirements, H/C role, u/c type, rotor blade thickness and flapping stiffness (hinged and hingeless rotor designs).

3.1.4 Fuel Load

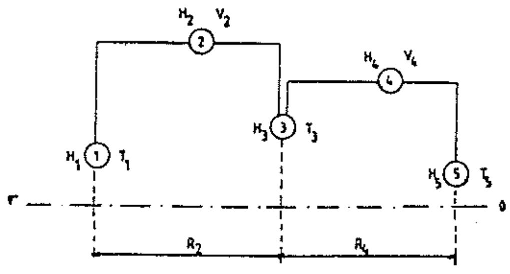
This is obtained from the equations

$$W_F = \sum_{K=1}^{5} F_K (W_{F_K}, P_K, S_K) \qquad \text{Eq.8}$$

$$S = S\left(f_e, \frac{P}{P_{ins}}, P_{ins}\right) x \qquad \text{Eq.9}$$

when x is an atmospheric factor and f_e is a factor to vary according to the type of engine installed.

Subscript K refers to the five stages contemplated in the generalised mission profile



The generalised s.f.c. vs Power vs Throttle Setting curves that Eq.9 describes correspond to rubberised versions of a current modern turboshaft.

The fuel consumed per stage W_{F_K} is evaluated in each case by iteration since, as equation 8 shows, W_F is an implicit function.

3.1.5 Required Power and Aerodynamic Performance

The required power for given atmospheric conditions, forward speed and aerodynamic loading, is given by equations

$$P_{req} = (P_{req_{MR}} + P_{req_{TR}})(1 + k_{TL}) \qquad \text{Eq.10}$$

$$P_{req} = \rho\sigma\pi R^2 V_T^3 \, q_c \qquad \text{Eq.11}$$

$$q_c = q_c(t_c, \lambda_{i_0}, \mu) \qquad \text{Eq.12}$$

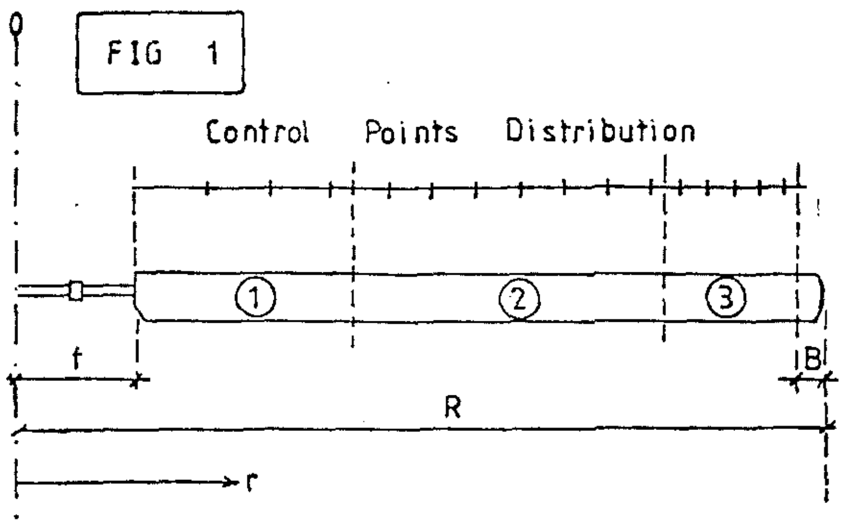
when k_{TL} is a factor due to transmission and cooling losses.

μ and t_c depend on α_{NF} and, hence, on the trimmed state of the whole H/C. These, and the in-plane force h_c equations together with the pitch angles to trim and the flapping first harmonics are evaluated by iteration.

The aerodynamic forces are evaluated using the BET approach[4,7,12]. The double integrals in azymuth and spanwise position can be evaluated analytically assuming mean aerodynamics ($\overline{C}_L$ and $\overline{C}_D$), or numerically where the blade aerodynamics are provided as tabulated functions of local incidence and M number. HELISOTON adopts both approaches assuming, in each case, an induced velocity field across the disc as proposed by Glauert.

When calculating the aerodynamic forces analytically, HELISOTON evaluates the localised effect of advancing blade compressibility and retreating blade stall by means of algorythms based on[5].

When using the numerical integration routines, HELISOTON can be used to evaluate the effect of non-linear washout and varying aerofoil sections along the blades. Currently, as many as three different blade sections can be distributed along the rotor span. HELISOTON concentrates a greater number of control points towards the rotor tip where the local dynamic heads are greater.



Both methods of evaluation of the aerodynamic forces take into account tip loss factors, root cut-out, real or virtual hinge offset and climbing/descending flight.

3.1.6 Trim

The pitching moment equation is linked to the orthogonal rotor forces (evaluated about the non-feathering axis). The tail plane contribution is evaluated by considering a local downwash model[6].

The rotor shaft tilt is chosen so as to give the H/C an attitude of 0 degrees in the hover.

The fuselage drag is evaluated by adopting the equivalent frontal drag area principle.

$$d_{c_{FUS}} = 0.5\rho\mu_1^2 \, d_x \quad ; \quad d_x = \frac{D_x}{\sigma\pi R^2} \qquad \text{Eq.13, 13a}$$

$$D_x = c'(W_T)e^{k'(W_T)} \qquad \text{Eq.14}$$

when c' and k' are parameters which depend on the fuselage aerodynamic cleanliness and are statistically related to the A.U.W. of the H/C.

The directional and lateral equations are solved as separate systems, again by iteration:

$$t_{c_{TR}} = t_{c_{TR}} (\ell_{TR}, \tau_{MR}, y_{c_{FIN}}) \qquad \text{Eq.15}$$

$$y_{c_{FIN}} = y_{c_{FIN}}\left(\beta, \frac{\partial y_{c_{FIN}}}{\partial\beta}, \tau_{MR}\right) \qquad \text{Eq.16}$$

$$\partial y_{c_{FIN}}/\partial\beta = f(\beta) \qquad \text{Eq.17}$$

$$A_1 = A_1(t_{c_{TR}}, \beta, A_1) \qquad \text{Eq.18}$$

$$\phi = \phi(A_1, \beta, \tau_{MR}) \qquad \text{Eq.19}$$

where τ_{MR} is the main rotor torque to be compensated by the tail rotor and the fin. Eq.17 indicates the masking effect of the fuselage wake on the fin A/D force.

The tail rotor is sized from using Eq.15 in the hover (giving a maximum loading to the tail rotor) in conjunction with the parametric relationships

$$\ell_{TR} = \ell(R, R_{TR}) \qquad \text{Eq.20}$$

$$R_{TR} = R_{TR}(t_{c_{TR}}) \qquad \text{Eq.21}$$

3.1.7 Parameter Limits

HELISOTON, in the course of the basic iteration loop, checks that the number of blades is a minimum of two and that the aspect ratio is limited to 22, a current technological limit from blade stiffness considerations.

The program also makes sure that adequate clearance exists between main and tail rotors that the tail plane is not loaded past $C_{L_{max}}$, and that the fuselage attitude in high speed cruise is not greater than $\pm 3^o$.

3.2 Stick Fixed Stability

Uncoupling the flapping equations from the overall H/C six degrees of freedom is justified[7,8] due to the comparatively small time constant of the very well damped flapping motion.

Uncoupling the longitudinal or lateral equations is justified, more with hinged than with semi-rigid rotors, on the grounds that small magnitude cross-coupling A/D derivatives give rise to negligibly small values for the coefficients associated with the cross-coupled modes.

Linearization of the equations is justified for small perturbations and, therefore, practicable for the stability analysis.

HELISOTON adopts this approach which is similar to that of[7]

$$[q_i] = [a_{ij}][e^{\lambda_j t}] \qquad \text{Eq.22}$$

when $i \in \{1,2,3\}$, $j \in \{1,2,3,4\}$

$$[a_{ij}] = F(\lambda_j \text{ A/D derivatives}) \qquad \text{Eq.23}$$

$$[a_{ij}] = c_4\lambda^4 + c_3\lambda^3 + c_2\lambda^2 + c_1\lambda + c_o \qquad \text{Eq.24}$$

and the λ_j stability roots are obtained from equating Eq.24 to 0.

The A/D derivatives are determined about the A/D wind axis.

3.3 Optimisation Operation

The program dismisses impossible values and attempts the sequential optimisation of the main rotor solidity, the main rotor blade mass, the main rotor hinge offset (flapping frequency ratio), the control sensitivity in roll and pitch and the tail-plane area.

3.3.1 Blade Loading/Solidity

The H/C gross weight, for a given specification, is very much linked to the main rotor blade area since this parameter appears in both the required power and the empty weight equations. The ratio of gross weight to blade area, or blade loading B_L, is hence the one parameter which bears directly on the convergence value of the gross weight.

For a given disc loading D_L , the variation of B_L is inversely proportional to the variation of the main rotor solidity σ

$$B_L = \frac{W_T}{\sigma \pi R^2} = \frac{D_L}{\sigma} \qquad \text{Eq.25}$$

HELISOTON seeks to reach an optimum value of σ by examining the rotor aerodynamic cleanliness both in hover and in forward flight. By aerodynamic cleanliness it is meant the degree of advancing blade compressibility and retreating blade stall extant at the checking conditions. These are quantified by means of ratios δ which are brought as close to unity as possible through changes in σ.

δ_{FC}, for example, is given by $\frac{C_D}{C_{D10}}$, where C_{D10} is the C_D associated with drag divergence due to shock wave formation (the point at which the shape of the C_D vs M curve reaches 10%). Subscript F refers to forward, C to compressibility.

Sometimes the δ ratios corresponding to hover and forward flight might be on opposite sides of the target. In that case, HELISOTON seeks to reach a condition when $|\delta_H - 1| - |\delta_F - 1| = 0$ Eq.26

3.3.2 Disc Loading

In order not to disrupt the σ optimisation process, the D_L checking is performed at a constant blade loading.

HELISOTON tries to match the power required to hover and the power required to achieve maximum forward speed by changing the disc loading. The slope of the P vs D_L curve is steeper for P_H than it is for P_F, so increments in D_L tend to close the gap between P_H and P_F (Fig.2).

A target 10% is set for the matching of P_H and P_F. This, however, might not be practicable if V_{max} is not very high and under certain input specifications/conditions, the closing of the P_H to P_F gap might lead to inordinately high values of the final gross weight. In such cases, HELISOTON overules the process and selects D_L so that W_T is minimised.

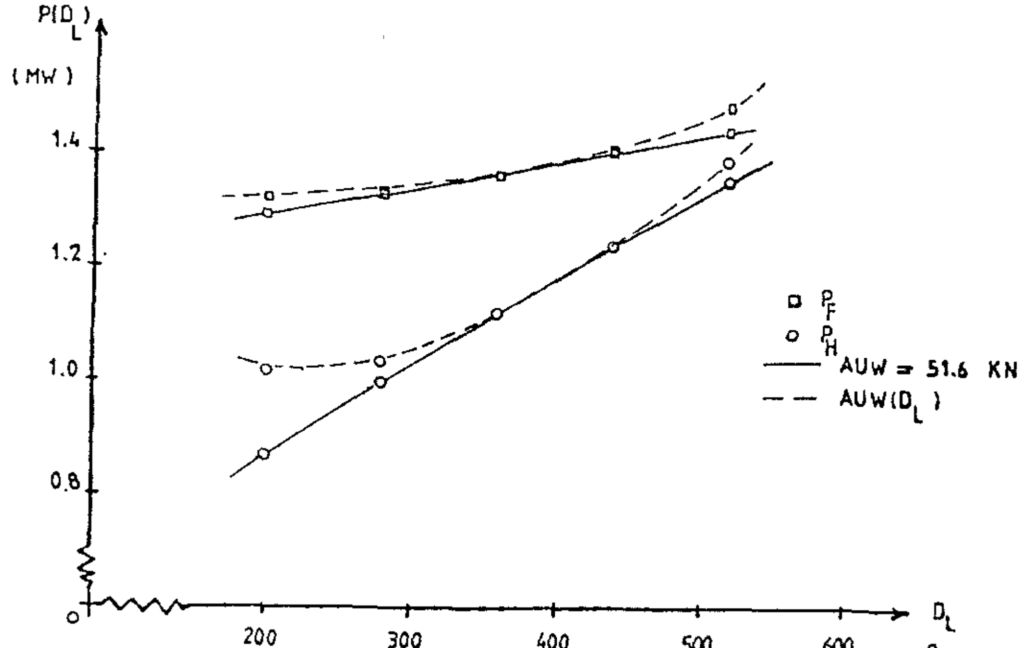


FIG. 2

3.3.3 Blade Mass

The main rotor inertia has a direct bearing on the aerodynamic flapping equations, the dynamic equations (hub moment component in pitch and roll), the empty weight equations and plays a fundamental role in the autorotation characteristics of the H/C.

HELISOTON checks that the ratio x of H/C translational energy to rotational energy[5] falls within limits leading to acceptable autorotative flare-out characteristics in the case of complete power failure. x is related to γ (Lock's number) and through this to the blade mass. If x falls short of requirements, extra mass is added to the main rotor blade tips to bring x within limits. This can be over-ruled by a consideration of the overall H/C damping (in roll and pitch) through the hub moment parameter $c_{m_s}(\gamma,\lambda_\beta)$ (see section 3.3.4.)

HELISOTON also computes the steady state terminal falling velocity v_c and the corresponding RPM. Forward speed is assumed to be that corresponding to minimum power flight.

3.3.4 Flapping Frequency Ratio, λ_β, Control Sensitivity.

λ_β is related to the H/C handling qualities (control sensitivity) because it features in the 'flapping' terms of the damping and the control power equations. λ_β is a more decisive contribution to the H/C handling qualities for semirigid rotors than it is for hinged rotors, although it still remains an important term in this case.

By changing λ_β, the H/C can be made to satisfy the constraints for minimum damping/inertia ratio postulated by[9].

For hinged rotors, λ_β is solely related to the flapping hinge offset. For semirigid rotors, λ_β is related to an equivalent hinge offset and a blade stiffness element m_β.

For hingeless rotors, HELISOTON assumes an equivalent hinge offset e' related to the extent of the root cut-out and calculates the remaining contribution to $\lambda_{\beta req}$ which will then be due to m_β.

For control power, HELISOTON adopts a gearing ratio related to the range of trimming angles A_1, B_1. If the control power thus calculated falls outside the zones of permissible control sensitivity as stipulated by Wernicke and Edenborough[10], λ_β is changed to meet the requirement. If this leads to the condition of minimum damping/inertia not being satisfied then γ is altered to meet the target. If the change in γ is associated with blade mass increments greater than 20%, then λ_β is reverted back to its original value and the control sensitivity condition is met by changing the gearing ratio.

Again, these tests are performed both for the hover and the maximum manoeuvre speed and for both rolling and pitching motions. If a compromise must be reached, HELISOTON makes sure that at least one of the hover and maximum manoeuvre requirements are met by the design.

3.3.5 Tail-Plane Area A_{TP}, Stability Criteria

The tail-plane area A_{TP} is related to both static and dynamic stability. HELISOTON over-rides static stability trim considerations and chooses A_{TP} so as to obtain a SPO*frequency parameter compatible with a Harper-Cooper rating of 3.5[11].

HELISOTON sets limits to the maximum value of this parameter to avoid an inordinately large T/P area.

The program also checks the NASA divergence criterion concerning both normal acceleration and rates of roll and pitch both for hover and maximum manoeuvre speed, and the constraints on the "plugoid" of the longitudinal motion[9]. These latter functions are passive modes.

3.3.6 Other Operational Capabilities

HELISOTON, in the 'design' mode, designs the broad layout of the interior of passenger carrying H/C (seats abreast, number of rows, cabin cross-section, aisles if any) on the basis of attaining an adequate fuselage finesse ratio for the given payload.

The program can also choose the right number of engines on the basis of either minimum bulk or minimum frontal area (according to the H/C role). For this HELISOTON uses statistical formulae of power plant dimensions as a function of installed power.

The program can activate a simple 'simulator' module to assess the H/C response during the first two cycles of both the high modulus root and the 'phugoid' or Dutch roll. In hover, or when one of the modes is non-

* high modulus root

oscillatory, the time parameter for observation is changed to the time to double or half amplitude.

When in print-out mode, finally, HELISOTON provides such performance parameters as the best cruising speed, minimum power speed, figure of merit in hover, disposable load/empty weight ratio, power/weight ratio and the forward speed spectrum of power, flapping angles, trim angles and excess power.

4. Sample Program Results

Figures 6 through to 16 have been obtained from the output of the program or some of its sub-routines. These figures are included in this paper with the purpose of illustrating the potentialities of HELISOTON and the several modes in which the program can be advantageously operated.

Fig.6 shows the optimisation path followed by the program for the selection of disc-loading and solidity. The input corresponds to a H/C of the search and rescue type. This graph also shows the blade loading limits of 3000 N/m^2 and 5000 N/m^2 and the aspect ratio limitations for different number of blades. The * denotes the design point of the baseline helicopter as given by the manufacturers.

Fig.7 shows a typical output of the program. This time the program was run in 'monitor' mode with input corresponding to a search and rescue H/C. The output corresponds to the aerodynamic analysis of the main rotor and displays the variation of required power, control angles and flapping angles across the forward speed range of the H/C at 500m ISA + 5^{o}C atmospheric conditions.

Fig.8 displays the effect of employing different aerofoil sections in the main rotor on the gross weight of the baseline H/C. The variation of this effect with maximum tip M number is also displayed. The input specification is the same as for Fig.7 . Curve A corresponds to the standard NACA 0012 section, Curve B corresponds to the RAE 9615 blade section whilst Curve C corresponds to a mixture of both sections, the higher lift, cambered, RAE 9615 section covering the innermost 30% and outermost 15% of the blade. It should be noticed the improvement in AUW derived from using the more modern RAE aerofoil and that, for a range of the design tip M, a combination of both sections would be more profitable.

Figures 9a and 9b depict the root loci variation with forward speed. The roots correspond to the solution of the eigen determinantal of the longitudinal stability equation for a H/C with characteristics similar to those of a current medium-sized transport. Fig.9a corresponds to an aft c.g. position relative to the shaft (c.g. offset) of 0.02R and a flapping hinge offset of 0.10 whilst Fig.9b refers to a forward c.g. offset of -0.02R and a flapping hinge offset of 0.05. In both cases the mirror conjugates of complex modes have been omitted and the righthand side and lefthand side of the imaginary axis have been scaled differently for convenience. The arrows indicate the directions of increasing forward speed.

Fig.10 shows the effect of altering the c.g. offset from -0.02R to 0.02R (0.02R) on the loci of the eigenvalues of the characteristic longitudinal stability equation. Inputs are similar to those of Fig.9.

The arrows indicate direction of increasing c.g. offset and labels a and b refer to flapping hinge offsets of 0.05 and 0.15. The forward speed considered is 100 Kt. It is to be noticed that for this trial, the case corresponding to a greater hinge offset displays a greater sensitivity to c.g. location than the smaller hinge offset case. The damping term of the high modulus roots is almost insensitive to c.g. location whilst for the small modulus roots it is the frequency term which is comparatively unaffected.

Fig.11 depicts the effect of flapping hinge offset (0.05→0.15 (0.05)) on the loci of the eigenvalues on the Argand plane. Inputs are similar to those of Fig.9. Two forward speeds are considered: (a) 100 Kt and (b) 140Kt. The deterioration of stability should be noticed for the small modulus roots as the hinge offset is increased. Increase in forward speed also produces a deterioration in stability of the "phugoid" roots. The c.g. offset considered is 0.0.

Fig.12 shows the effect of flapping hinge offset and forward speed on the control sensitivity. The input corresponds to an entirely hypothetical baseline H/C. The range of forward speeds is 0,160 (40) Kt. Also shown on the graph are the control sensitivity requirements as postulated by[10,14] and the minimum required damping/inertia ratio as stipulated by Mil. Spec. 8501A[9]. The gearing ratio considered is 2rad/m and the figure shows longitudinal characteristics of the base-line model. It should be noticed that large gains are possible, particularly in control power when the flapping hinge offset is increased. The outward swing of the curves towards greater control power as speed is increased with flapping hinge offset is also evident and consistent with greater hub static moments.

The baseline model just fails to reach the band of acceptable control sensitivity margins for the cases of greater hinge offset e for the given gearing ratio, and it exceeds the permissible bounds for e = 0.05 at both ends of the speed range.

Fig.13 refers to the same baseline model of Fig.12. The graph indicates the affect of combinations of c.g. offset and e on the control sensitivity of the H/C. Again, a gearing ratio of 2 rad/m has been adopted and 2 forward speeds examined, 60 kt and 160 Kt. The graph also shows the same control sensitivity boundaries of Fig.12. The baseline model falls in the acceptable band only for e = 0.10 for all values of the c.g. offset when V = 60 kt. The c.g. offset has a greater influence on the low speed case than on the high speed case. This suggests the possibility of c.g. shifts in flight to meet varying operational conditions.

Figures 14 through to 16 are monitoring studies of a baseline H/C with mission requirements and task similar to those of a current search and rescue H/C.

Fig.14 depicts the effect of blade loading and disc loading on the AUW and the A/D cleanliness of the main rotor. The parameter δ_{FS} indicates how close to the stalling the most severely affected spanwise station of the retreating side of the rotor is when the H/C is flying at maximum gross weight and maximum forward speed. The compromise between AUW and A/D cleanliness is apparent as is the general trend to heavier design with increasing D_L at constant B_L. This is due to higher induced velocities that penalise the hover performance and increase the installed power. A phenomenal increase in AUW for the lower blade loadings is associated with the penalties incurred by having inordinately large rotors.

Fig.15 shows the effect of tip Mach number and linear twist on the design. Higher AUW values are derived at higher tip Mach numbers due to the onset of compressibility. At lower M (0.7), however, the losses due to retreating blade stall are so great that the installed power pushes the AUW upwards. The beneficial effect of blade twist in the alleviation of A/D uncleanliness is striking, particularly for M = 0.7 when drastic reductions in AUW result from applying washout to the blades. The parameter δ_{FC} refers to the ratio of drag coefficient to drag divergence coefficient in the advancing blade. As expected, it increases with M_{TIP}.

Fig.16 depicts a trade-off between payload and range. Two cases are considered: (a) the basic baseline H/C and (b) a heavier H/C with different, less efficient engines. The latter shows in the slope of the payload/Range curve. Both models have the same fuel tankage limit but the heavier H/C has a greater payload storage capacity.

5. Concluding Remarks

5.1 General

This paper presents a limited description of HELISOTON which, although operational, is by no means complete. The program is being constantly updated in the light of further analytical work and the continuous comparison of program outputs with available new experimental data.

The program capabilities will be extended further with the introduction of newer algorythms. Future developments contemplate the possibility of adding a simple economics module to the optimisation loops, extending the aerodynamics package to perform simple harmonic blade load analysis to permit the determination of the number of blades and to devise optimisation loops for the maximum tip M number (compromise between performance, economics and dynamics) and the main rotor twist (washout profile).

5.2 Exactness vs Time-Efficiency

It is evident that a compromise must be reached between rigorousness of analysis and computational time efficiency. HELISOTON offers a solution to this compromise, leaning mostly towards the side of computational efficiency.

Some of the points sacrificed for the sake of computational efficiency are:-

a) convergence guarantee: the program will quickly converge for most cases. A guarantee of convergence for all cases would imply the solution of what is the basic iteration block by means of methods using the Jacobian matrix of the non-linear equations, which is computationally time consuming;

b) optimisation guarantee: the use of nested- loop optimisation techniques lead necessarily to partial optimisation. The use of a multi-variable optimiser parameter $P(x_1, x_2, \ldots x_n)$ could guarantee a definite point of optimisation over all x_n variables but it would imply massive running times. Furthermore, in view of the simple assumptions made, it is doubtful if this 'optimised' solution would have any physical significance except to identify an area of solution in which the final design will lie.

c) aerodynamic detail: HELISOTON employs the BET approach of solution of the aerodynamic forces. The method is relatively fast and is amenable to the analysis of localised phenomena such as local drag divergence and local blade stall but it relies on a prescribed wake. The use of non-prescribed wake techniques would make the program prohibitively expensive to run. The BET approach invalidates any attempt to analyse rotor/fuselage interaction, main rotor/tail rotor disturbances, blade/vortex interactions, blade local sweep effects, etc;

d) dynamic analysis: The use of the linearised model prevents the analysis of the response of H/C performing high g manoeuvres. The use of uncoupled equations invalidates, to a certain extent, the stability analysis of the semi-rigid rotors when a significant amount of roll/pitch coupling can be expected[13].

e) H/C mass distribution: although the models described in Fig.5 are expected to cover most conventional H/C shapes, a much more detailed approach would be needed in the light of testing that shows that the algorythms overestimate consistently the second moments of inertia. Again, increasing the complexity of the analysis (the number of identifiable mass units) would be detrimental to time-efficiency.

Despite these shortcomings, the scope and usefulness of the program covers an extensive field of activities in which the designer can find himself at the preliminary stages of design synthesis.

5.3 Conclusions

a) The application of digital computers to baseline helicopter design can be achieved efficiently and is entirely feasible.

b) Any program developed for this purpose will necessarily have to reach a compromise between exactness of analysis and computational time-efficiency.

c) The path along which the final baseline design is reached can be indicated by use of programs such as HELISOTON.

d) Design trade-off relationships between the various significant design parameters can be readily determined.

e) The effect of airworthiness design criteria can be ascertained on a particular design.

f) The effect of applying criteria belonging to a design discipline on criteria belonging to another design discipline can be easily determined, i.e. dynamic on aerodynamic.

g) The use of the same master core determines that a program developed to perform design synthesis tasks can be promptly adapted to perform routine design analysis duties.

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NOTATION

Abbreviations

ASW	antisubmarine warfare
AUW	all up weight
A/D	aerodynamic(s)
BET	blade element theory
c.g.	centre of gravity
CPU	computer occupancy time
H/C	helicopter
ISA	international standard atmosphere
NAG	National Algorythm Group
PPA_n	Procurement Executive
RPM	revolutions per minute
S.I.	Systeme International
S&R	search and rescue
u/c	undercarriage

Symbols

a_{ij}	generalised j coefficient of q_i
A_1	lateral control angle
B	tip loss factor
B_1	longitudinal control angle
B_L	blade loading
c_n	coefficients of the dynamic determinantal
C_D	lift coefficient
C_L	drag coefficient
C_{ms}	hub static moment
D_L	disc loading
D_x	equivalent frontal drag area
e	flapping hinge offset
f	root cut-out
H	altitude
h_c	in-plane force coefficient
I	second moment of inertia
k	dummy parameter
ℓ	length parameter
M	Mach number
m_β	blade stiffness parameter
P	power
Q_c	torque coefficient
q_i	generalised displacement
R	rotor radius
r	rotor radial station
s	s.f.c.
T	time on station
t_c	thrust coefficient
V	forward speed
V_T	tip velocity
V_c	terminal falling speed
W	weight
x_{cg}	'x' c.g. position
X	position of mass in mass distribution model
y_c	side force coefficient
α	angle of incidence
β	sideslip angle
δ	generalised A/D ratios
ϵ	$(1+\epsilon)$ = first to second flapping inertia ratios
θ_0	collective pitch angle
θ_x	twist
λ_j	j eigen value
λ	Lock's number
λ_β	flapping frequency ratio
μ	advance ratio
ψ	azimuth angle
ρ	atmospheric density
ϕ	roll angle
σ	solidity
τ	main rotor torque

Subscripts

C	compressibility
DIV	drag divergence
E	empty ; engine
F	forward ; fuel
H	hover
ins	installed
md	mass distribution
mp	mission profile
nf	non-feathering axis
P	payload
R	rotor design (existence of flapping hinge)
req	required
S	stall
T	total ; tip
TP	tail plane
TR	tail rotor
x	spanwise station

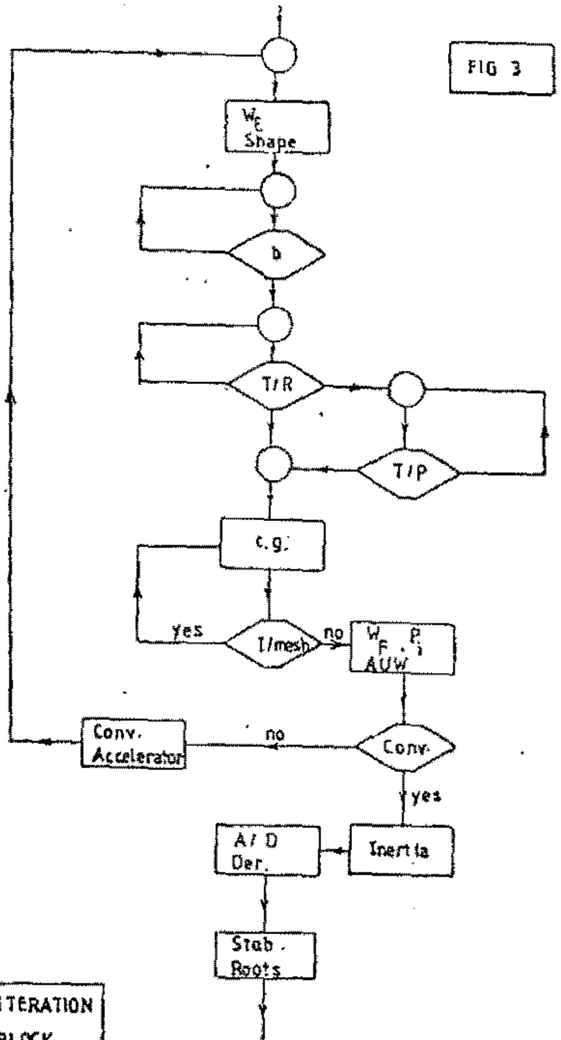


FIG 3

ITERATION BLOCK

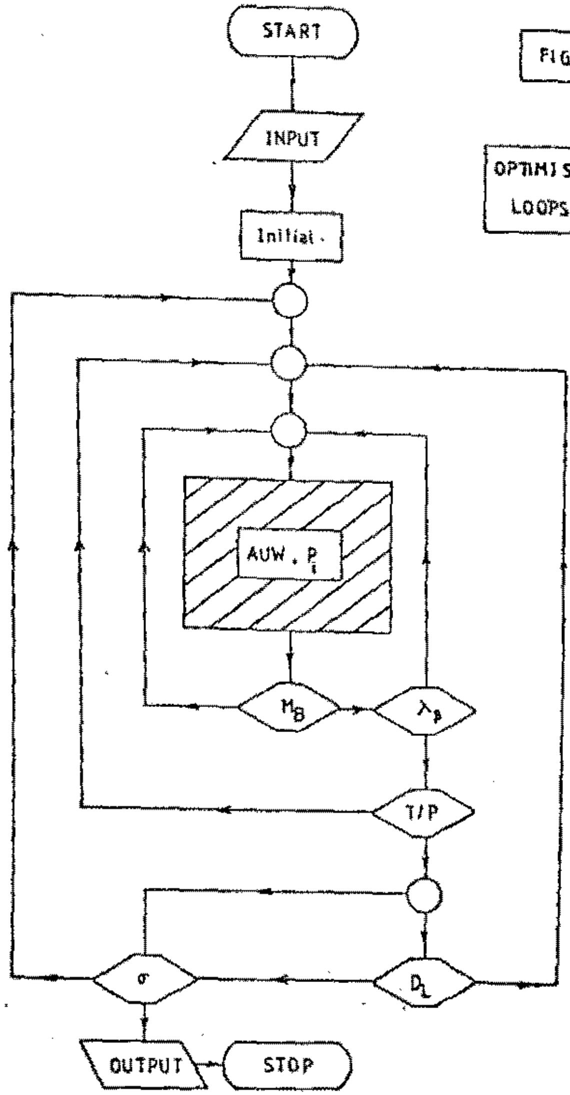
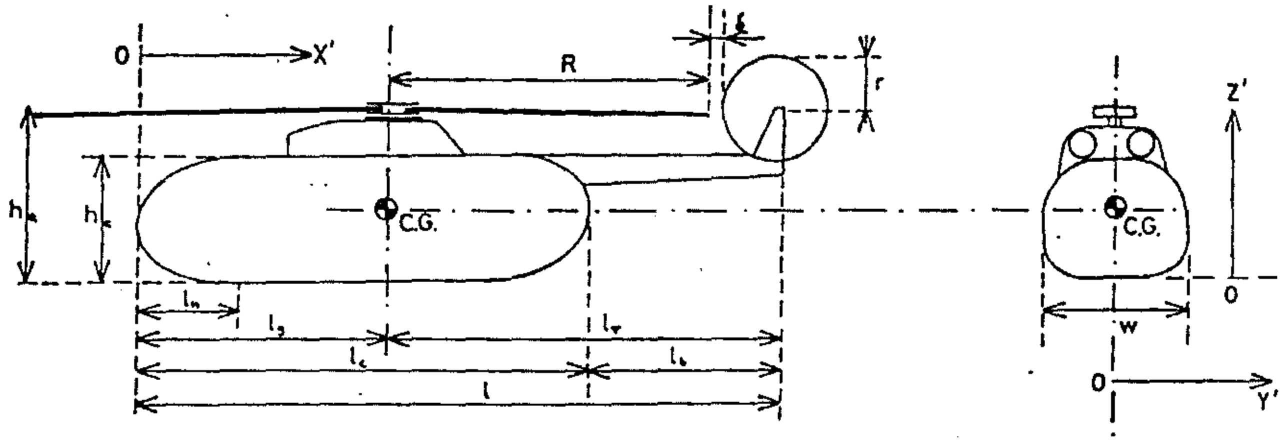


FIG 4

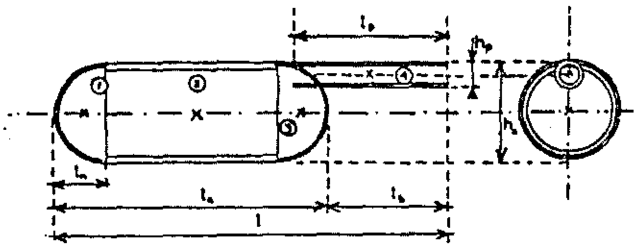
OPTIMISATION LOOPS

FIG. 5

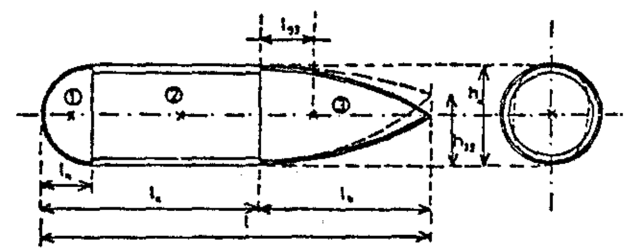
FG1 GENERALISED HELICOPTER DIMENSIONS



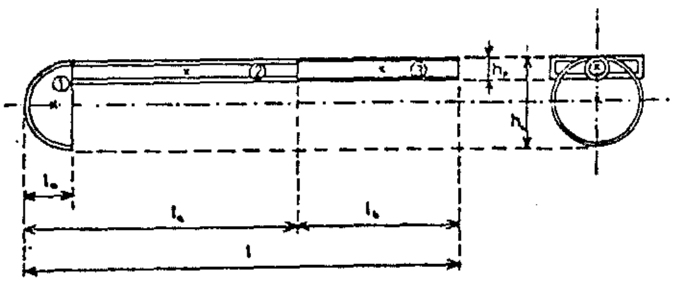
FG2 PASSENGER-CARRYING H/C



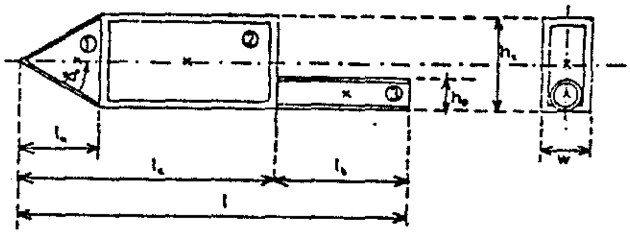
FG3 SEARCH&RESCUE H/C



FG4 SKY-CRANE HELICOPTER



FG5 ATTACK HELICOPTER



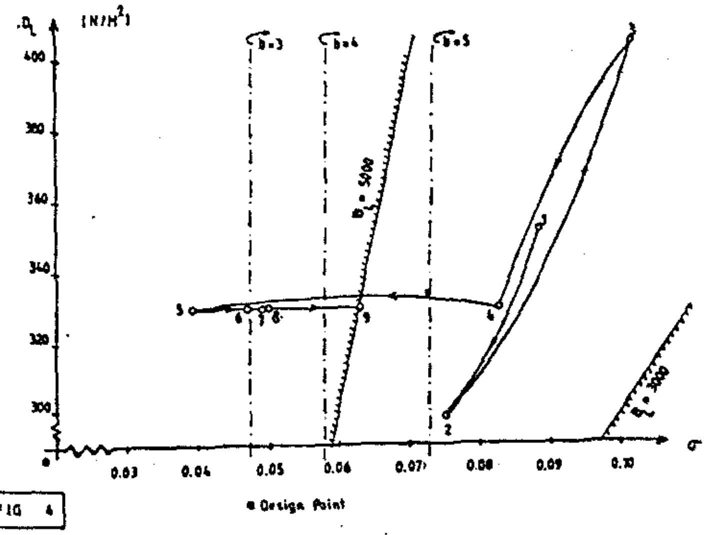


FIG 6

• Design Point

MAIN ROTOR PARAMETERS

FORWARD SPEED (KNOTS)	POWER (MW)	THETA (	A0	A1 DEGREES	B1	Σ B1	A1 3 CYCLIC PITCH) TO TRIM
0.0	1.5679	15.876	9.776	0.111	4.111	-0.689	3.055
10.0	1.4796	15.137	9.564	0.639	4.080	0.126	4.332
20.0	1.3331	14.605	9.372	1.099	3.826	0.713	4.071
30.0	1.1472	13.614	9.116	1.498	3.464	1.086	3.658
40.0	0.9900	12.997	8.890	1.865	3.181	1.321	3.118
50.0	0.8761	12.625	8.723	2.231	3.029	1.497	2.695
60.0	0.7970	12.452	8.605	2.610	2.981	1.655	2.421
70.0	0.7621	12.441	8.525	3.010	3.003	1.817	2.271
80.0	0.7042	12.565	8.473	3.437	3.071	2.010	2.214
90.0	0.6806	12.818	8.446	3.897	3.171	2.266	2.234
100.0	0.6764	13.168	8.438	4.401	3.276	2.590	2.330
110.0	0.6822	13.675	8.448	4.949	3.432	3.011	2.516
120.0	0.6956	14.281	8.474	5.547	3.560	3.550	2.768
130.0	0.7160	15.008	8.514	6.201	3.736	4.229	3.086
140.0	0.7512	15.868	8.568	6.913	3.896	5.085	3.470

FIG 7

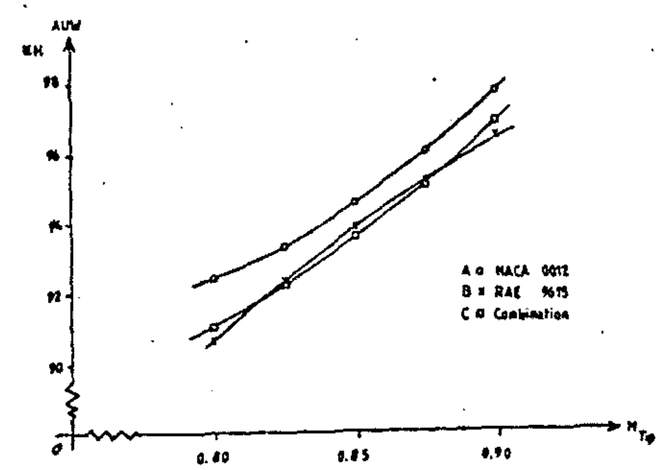


FIG 8

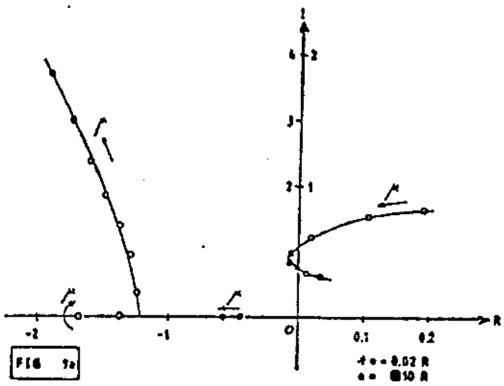


FIG 9a

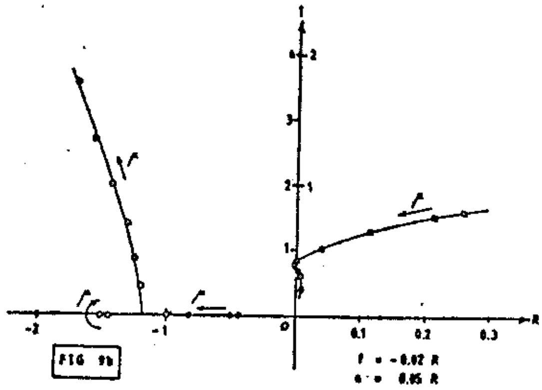


FIG 9b

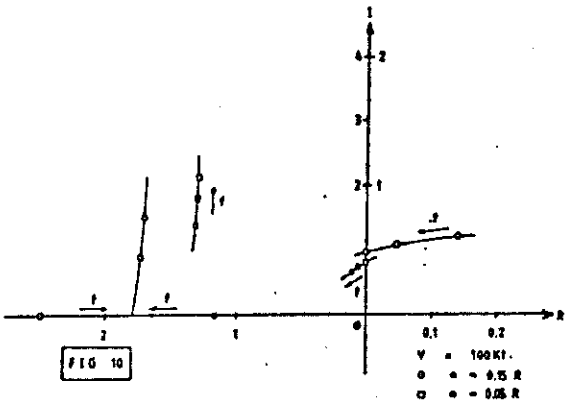


FIG 10

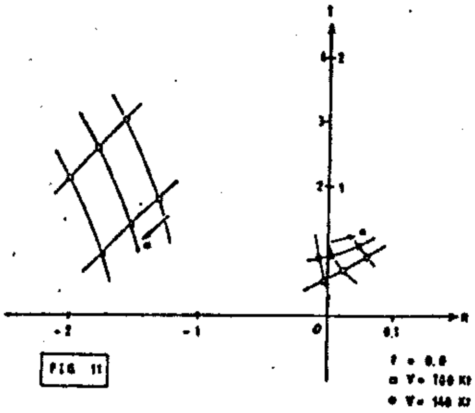


FIG 11

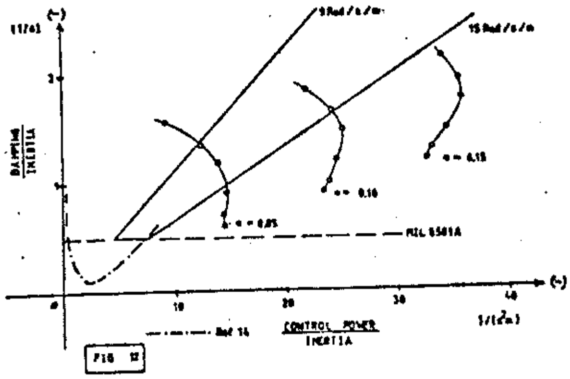


FIG 12

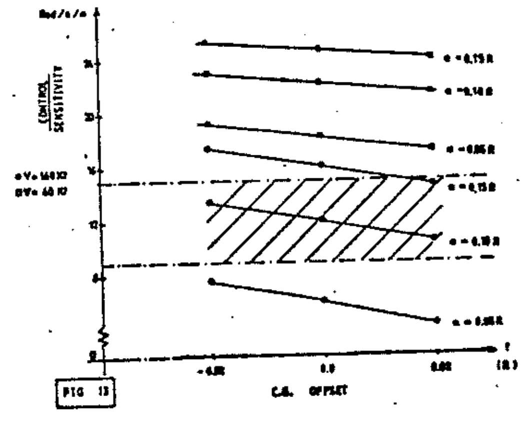


FIG 13

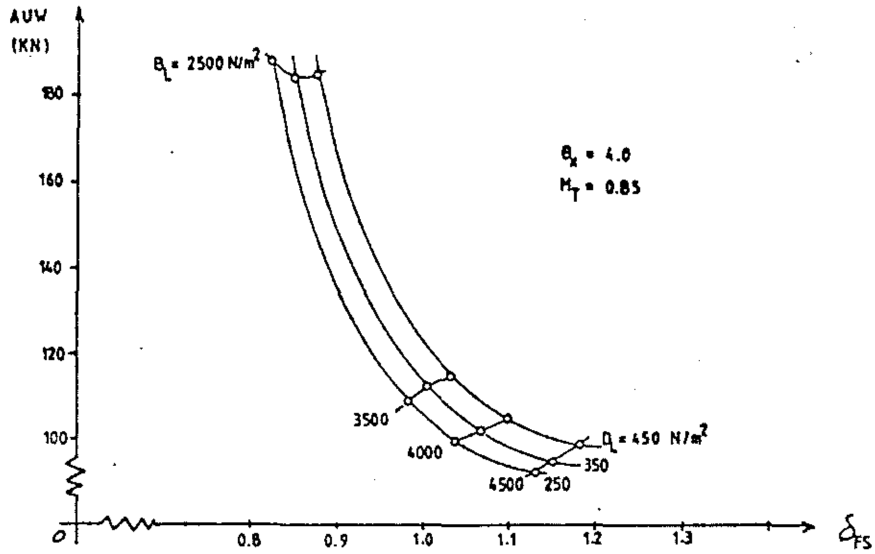


FIG 14

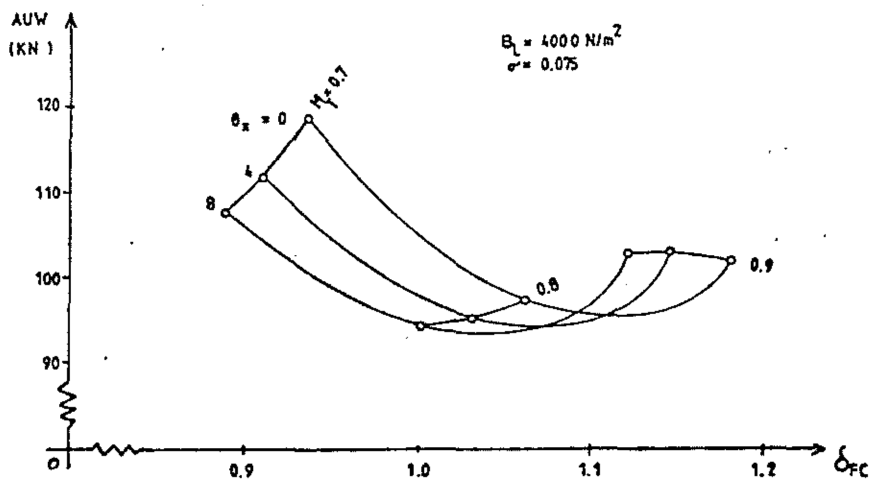


FIG 15

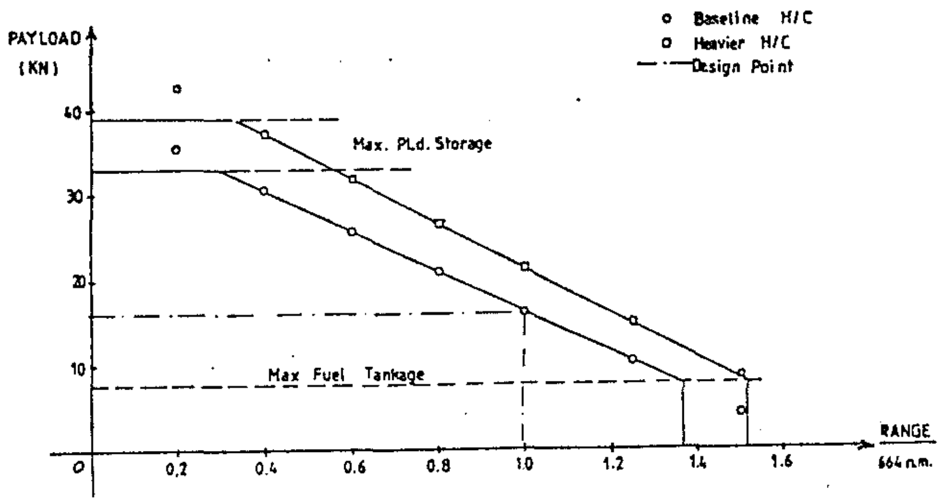


FIG 16