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DEVELOPMENT OF GENERIC HELICOPTER PERFORMANCE METHODOLOGY FOR REAL TIME MISSION ANALYSES

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Abstract

This paper describes the methodology and technical approach used to develop a portable mission performance and planning computer for military helicopter operations. Advanced developments in microprocessor technology, software language, and mathematical techniques are combined to offer a highly sophisticated system which is pilot friendly, lightweight (one pound), compact in size, high speed, and has communication interfaces for ground-based or on-board mission processors. The Computerized Handheld Integrated Mission Performance (CHIMP) system has been developed for a variety of USMC and USA helicopters. CHIMP's flight management system functionality integrates comprehensive helicopter performance, operating limitations, navigation, and weight and balance capabilities.

1. Introduction

This paper provides a panoramic view of the integration of various technologies which combine to offer a unique mission management system for helicopters. Emphasis is given to the development of semi-empirical algorithms which determine helicopter performance and operating limitations.

The USA is currently developing an automated ground-based mission planning system for operations on the Dolch 80486-based computer. While this system is considered to be portable, it is too cumbersome and heavy to be practically used on-board the aircraft. A Data Transfer Module (optical disk) is used to up/down load data between the Dolch and the aircraft. The Army-developed system represents a technology leap compared to existing Navy and Air Force systems. However, not all operations require the comprehensive capabilities nor may the system be readily available for austere operations. Therefore, the CHIMP system has been developed to fulfill special assignments when other systems may not be practical or available.

CHIMP provides military pilots with a low cost, lightweight, straight-forward approach to electronically conducting mission planning and performance. CHIMP significantly reduces pilot workload during preflight planning or amended en route clearances. Additionally, CHIMP incorporates similar mission performance technologies and Graphical User Interface (GUI) as with the Army's ground-based system. CHIMP can be used as an interface with existing ground-based or on-board mission planning systems or as a separate "stand alone" system which can be carried in the flight suit pocket.

Figure 1 provides a computational flow chart of CHIMP development. Assimilated flight test and engineering data are analyzed using the Aircraft Performance Evaluation Computer Program (APECOMP), developed by Praxis Technologies Corporation and currently used for US Army and Navy applications. Separate software load modules are

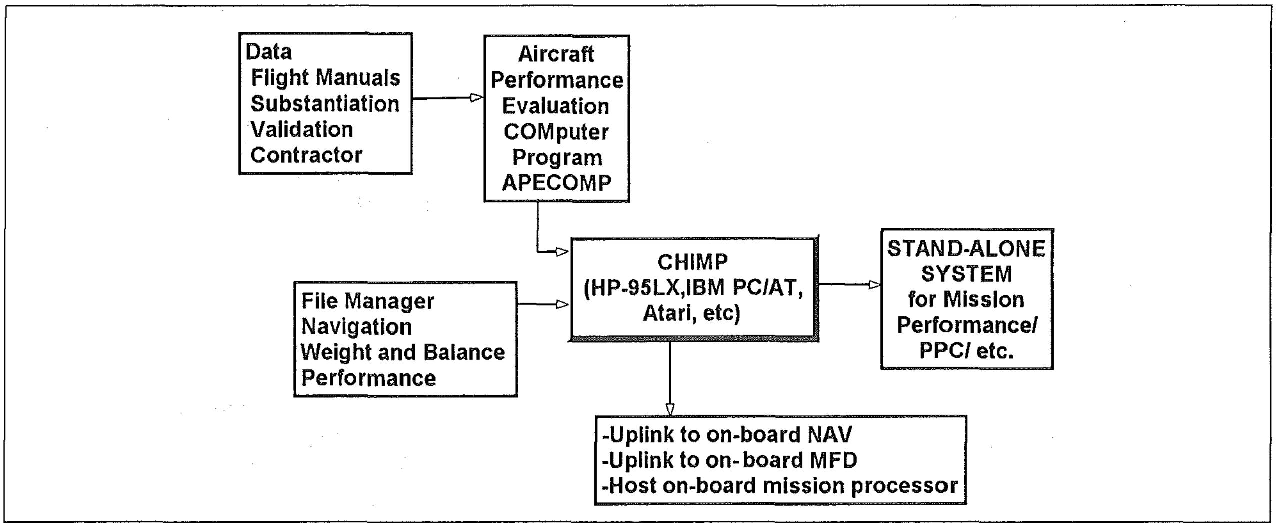

Figure 1. CHIMP Computational Flow Chart

incorporated into CHIMP for conducting weight and balance, navigation, file management, and mission performance. CHIMP can export data directly to a printer, or via RS-232 cable, can uplink to the aircraft or to external systems such as ground-based mission planners or desktop computers.

The most prominent technical feature of CHIMP is its unique analytical approach for estimating generic helicopter performance. This approach was developed by Praxis Technologies Corporation and is based upon semi-empirical helicopter rotor theory using the extensive military flight test database. The technical approach presented herein offers several advantages over current mission performance methodologies; compact program size, speed, minimal block data storage, data extrapolation, and easy interface.

Typical use encompasses examining helicopter requirements or capabilities as a function of airspeed, ambient conditions, tip speeds, scavenge, accessory losses, rate-of-climb, aircraft configuration, and limits. Additionally, the methodology permits reasonable data extrapolation for examining the effects of perturbations in operating transmission limits, engine TOT, and tip speed.

2. Mission Management Requirements

Before CHIMP was developed, a comprehensive review of available mission planning systems was conducted. All systems were examined regardless of their size and complexity and a requirements list was established for CHIMP. The following design specifications were deemed necessary for successful system:

- Non-Developmental Item (NDI) which is low-cost, light-weight (1.0 LB), compact (palm size), and calculates in real-time
- Single system for all single and tandem rotor helicopter configurations
- Extremely user friendly
- Provide complete mission performance, navigation, and weight & balance
- Compatible with world-wide NAVAID database (Jeppeson-Sanderson)
- High fidelity (RMS less than 2.0 percent)
- Common software architecture for interface with other ground-based or on-board systems
- Portable software to run on variety of hardware platforms
- Provides all military charts, procedures, check lists
- Limited data extrapolation for special operations
- Flight Procedure Checklists
- Expandable to determine Maneuverability & Agility (Contour, NOE) flight capabilities

3. Analytical Techniques for Helicopter Performance

3.1. Introduction

There exist various theoretical approaches to assessing helicopter performance ranging from empirical to extremely comprehensive theoretical techniques. The more sophisticated analyses are generally used to describe the rotor system aerodynamics (compressibility and blade stall) and dynamics (higher harmonics), but can also be applied to the airframe and propulsion systems.

A Best Technical Approach (BTA) was selected based on classical (simplified) helicopter theory and empirical data. However, the simplified helicopter theory approximation is at best valid for only certain operating conditions and only to first order effects. To improve the fidelity of the predictive methodology a semi-empirical technique is developed using a substantial helicopter flight test database. These data are used to semi-empirically "fit" the classical helicopter theory to actual flight test data. Mathematical reduction techniques such as Singular Value Decomposition are used to develop a smooth and continuous set of equations which completely define the helicopter performance characteristics for any operating conditions. Additionally, CHIMP has provisions to determine helicopter operating limitations including One Engine Inoperative, Directional Control Margins, Never Exceed Airspeeds, Mach Limit Airspeeds, Load Factors, Height-Velocity, Transmission and Engine Limits, and Rotor Aerodynamic Limits.

This approach eliminates bulky tabularized databases, significantly reduces computational time, and provides generic methodology for both tandem and single rotor pure and compound helicopter configurations. Also provided are reasonable extrapolated performance estimates for perturbations in operating limits.

These mathematical techniques are incorporated into the Aircraft Performance Evaluation Computer Program (APECOMP) which is a preprocessor computer program developed by Praxis Technologies Corporation. APECOMP permits significant reductions in database storage and processor requirements through development of a sophisticated equation set which, in turn, makes CHIMP technically possible.

3.2. Assumptions

To establish various helicopter performance parameters it is imperative to first establish the total power required for given flight condition(s). This is determined through an integrated approach to assessing helicopter main and tail rotor powers required for single rotor helicopters.

Helicopter total main rotor power required as defined by classical helicopter theory is a summation of several contributing powers which include induced, profile, parasite, and non-uniform downwash. The total tail rotor power required is a function of the main rotor torque, blade aerodynamics, blade area, and fin blockage. The technical approach used for assessing the main rotor system is applied to the tail rotor system with simple redefinition of certain variables.

Generally, during flight test total helicopter power required is measured, not individual contributions from main and tail rotors. Power required is typically deduced by measuring the engine output shaft torque. This measurement accounts for engine installation, transmission, and shafting losses. Power required correction factors are applied to the summed total of main and tail rotor contributions. Accessory horsepower losses are included as part of the total power required.

Provisions are made to unload the main rotor lift by using a wing. Trending analyses are used to determine the wing profile drag and efficiency. This approach is also applied to assessing the contribution of vertical tail aerodynamics to anti-torque thrust.

Because of limited acquired data during flight test, certain assumptions are accounted for either by input or by equation design. More comprehensive test data permits greater accuracy in predicting flight performance conditions.

3.3. Development of Power Required

The equations defining the power required are dependent upon several operating conditions to include pressure altitude, free air temperature, rate of climb, airspeed, wheel/skid height, and associated losses. Currently, algorithms are provided for single rotor helicopter analysis only, separately examining hover (to include ground effects), cruise, and transitional flight. The power required algorithms constitute a significant portion of computer coding and are generally assessed as the highest priority calculations. Additional performance information of interest is determined after the power required is determined.

It is noteworthy to mention that accessory power extraction (losses) are accounted for by adding to the the power required as opposed to subtracting from the power available. This approach permits direct computation of fuel flow as affected by total power required.

The equations defining the power required contribution for the main and tail rotor systems have been generically defined to simplify the computer coding. Additionally, the equations have been non-dimensionalized to permit combining hover and forward flight algorithms. Over simplified, the power required equations are semi-empirically developed using a combination of individual power contributions and flight test data which serves to "correct" the theoretical analysis. This approach permits high fidelity answers when calculating performance specific to the helicopter input database. Small perturbations in operating and design limit conditions have been favorably compared with the Advanced Rotorcraft Sizing and Performance (ARSAP) computer program, a proprietary development of Praxis Technologies Corporation and with the Helicopter Sizing and Performance Computer Program (HESCOMP), a joint development of NASA/NAVY/Boeing.

3.3.1. Main Rotor Power Required

The non-dimensionalized value of total power required can be expressed as:

$$C_{P_{TOT}} = C_{P_{MR}} + C_{P_{TR}} + C_{P_{\Delta ACC}} \qquad (1)$$

Unless specified elsewhere the non-dimensionalized coefficients have been derived by dividing forces by $\rho * A_{MR} * V_{T_{MR}}^2$ and powers by $\rho * A_{MR} * V_{T_{MR}}^3$.

The main rotor power required can be divided into the following four elements:

1. Profile Power - the power required to turn to rotor
2. Induced Power - the power required to generate rotor lift
3. Parasite Power - the power required to provide propulsive thrust for forward (rearward) flight
4. Non-uniform Downwash Power - the power correction due to non-uniform inflow and downwash effects in forward flight

The main rotor power required can be written in non-dimensional form as:

$$C_{P_{MR}} = C_{P_{MRPRO}} + C_{P_{MRIND}} + C_{P_{MRNUD}} + C_{P_{MRPAR}} \qquad (2)$$

The tail rotor is similar to the main rotor in that it "flies" edgewise with respect to the free stream wind. Even though the tail rotor is at 90 degrees, or some other angle, to the main rotor, it can still be assessed using a similar approach. However, it is assumed that the tail rotor does not produce any propulsive thrust, therefore the tail rotor parasite drag contribution is zero. The tail rotor power required can be expressed non-dimensionally as;

$$C_{P_{TR}} = C_{P_{TRPRO}} + C_{P_{TRIND}} + C_{P_{TRNUD}} \qquad (3)$$

The accessory power loss accounts for main rotor gearbox power extraction necessary for various subsystems as air conditioning, electrical generators, and hydraulic pumps and is included in the total power required. The accessory power loss is non-dimensionalized by the main rotor parameters as

$$C_{P_{\Delta ACC}} = \frac{550 * (AccessoryHorsepowerLoss)}{\rho * A_{MR} * V_{T_{MR}}^3}. \qquad (4)$$

The total calculated power required equations are theoretically derived and then empirically corrected using flight test data.

$$C_{P_{TOTAL}}(actual) = K_1 * C_{P_{CALC}} \tag{5}$$

where K_1 is applied to the derived main and tail rotor powers required such that

$$C_{P_{TOT}} = K_1 \left[C_{P_{MR}} + C_{P_{TR}} \right] + C_{P_{\Delta ACC}}. \tag{6}$$

In hover, the rotor power required is composed of only two elements, the induced and profile powers. The induced power is adjusted for non-uniform inflow and wake contraction effects and theoretically is a function of rotor thrust coefficient and blade design. The profile power required is a function of the integrated blade drag coefficient including compressibility effects at a specified operating thrust loading.

In cruise, the induced power contribution is a function of the thrust loading, airspeed, rotor RPM, blade tip losses, and other losses. An induced power correction factor is applied based upon an empirically derived wake separation angle. This wake separation angle is a function of the main rotor design parameters and the hover power required.

The cruise profile power term is a function of the integrated blade drag coefficient corrected for compressibility and retreating blade stall effects at specified operating conditions and blade design parameters.

The cruise parasite power contribution is a function of the propulsive thrust required and the associated efficiency of the rotor to convert power into lift. The propulsive thrust is predominantly a function of the overall vehicle drag referred to as flat plate effective area. The parasite power is empirically corrected for forward flight airspeed and rotor operating conditions.

The non-uniform downwash power correction term for forward flight is a correction factor which has been empirically derived from a comparison of uniform and non-uniform downwash rotor analyses.

Within the equations for both hover and cruise powers required exist an induced power correction factor. This correction factor includes a term identified as K_{HOV} and is a function of the rotor lift. When assessing the hover flight condition, the rotor lift is equal to the rotor thrust, hence either term can be used. However, when assessing the cruise flight condition, the rotor lift is not equal to the rotor thrust, requiring K_{HOV} for cruise to be dependent upon C_T'.

The following approach illustrates the equations involved in determining rotor power required. For simplicity, the equations are presented with reference to the main rotor system but they are also applicable for assessing the tail rotor system.

The main rotor lift is generally equal to the weight of the helicopter. The main rotor thrust in hover would be equal to the lift plus associated download attributed to the presence of the fuselage and other components in the downwash of the rotor flow field. However, some helicopters such as modern combat attack configurations have a stub wing for stores carriage. This wing also provides additional lift as a function of airspeed and can "unload" the rotor of its overall lift requirement. Unloading the rotor has several advantages predominantly permitting more thrust available for forward flight propulsion. The disadvantage of a wing is its associated profile and induced drag. This additional drag has the overall effect of increasing the total propulsive force required for a given airspeed. Hence, adding a wing is not always advantagous. The vertical tail effects can be assessed in a similar manner as the main wing.

The equations have been developed to permit assessment of an existing wing, modified wing, or inclusion of a wing if not currently installed. Trending analyses are included in determining the wing efficiency and the profile drag as a function of the wing aspect ratio and lift coefficient, respectively.

non-dimensionalized rotor propulsive force:

$$C_{X_{MR}} = \tfrac{1}{2} * \mu_{MR}^2 * \frac{Fe}{A_{MR}} \tag{7}$$

A numerical iteration technique looping equations (8), (9), (10), and (11) is used to determine the non-dimensionalized total rotor thrust as a function of the induced velocity, wake skew angle, rotor lift, propulsive force, and operating conditions. Initially, the total rotor lift coefficient (C_{TMR}') is set equal to C_L.The forward flight non-dimensionalized induced velocity is defined as:

$$\bar{v}_{i_{MR}} = \left[\frac{(\mu_{MR}^4 + C_{T_{MR}}{}^2)^{1/2} - \mu_{MR}^2}{2} \right]^{1/2} \tag{8}$$

main rotor wake skew angle:

$$\varepsilon_{MR} = \tan^{-1}\left(\frac{2 * \bar{v}_{i_{MR}}}{\mu_{MR}} \right) \tag{9}$$

rotor lift coefficient:

$$C_{T_{MR}} = C_L \left(1 + D_{L_{wing}} * \sin^2\varepsilon \right) \tag{10}$$

Note, the $D_{L_{wing}}$ term includes the download on the entire wing/fuselage system, not just the wing. The subscript wing is selected such that when the tail rotor is analyzed the "wing" value is replaced with the "vertical tail" value.

The non-dimensionalized total rotor thrust is computed from:

$$C_{T_{MR}} = [\, C'^{2}_{T_{MR}} + C_x{}^2 \,]^{1/2} \tag{11}$$

From equation (2) the total main rotor power required is divided into four primary contributing factors. Each of these contributing power terms are developed separately.

The main rotor profile power can be estimated by:

$$C_{P_{PRO_{MR}}} = \frac{C_{D_{0_{MR}}} * \sigma_{MR}}{8} * (\, 1 + 4.65 * \mu^2_{MR} \,)\,(\, 1 - x^4_{C_{MR}} \,) \tag{12}$$

C_{D0} is the baseline main rotor blade profile drag coefficient and may not be readily identifiable in the data substantiation reports.

In order to calculate the induced power contribution it is necessary to first determine the induced power correction term (K_{IND}) which is an adjustment for non-uniform inflow and wake skew angle effects (K_{HOV}).

The induced power correction term is calculated as:

$$K_{IND_{MR}} = 1.1 * \cos^2 \varepsilon_{MR} + K_{HOV} * \sin^2 \varepsilon_{MR} \tag{13}$$

The non-uniform inflow and wake skew angle effects are corrected by various K_{HOV} parameters which are determined for the individual in- and out-of-ground-effect flight conditions. Idealistically, for both hover and cruise, K_{HOV} would be applied only to the induced power terms. For hover, the total power required can be written as

$$C_{P_{HOV}} = K_1 * [\, C_{P_{MR_{PRO}}} + C_{P_{MR_{IND}}} * K_{HOV_{MR}} + C_{P_{TR_{PRO}}} + C_{P_{TR_{IND}}} * K_{HOV_{TR}} \,] \tag{14}$$

Note, the K_{HOV} terms for main and tail rotor systems are actually different. However, there does not exist enough information to ascertain individual rotor system values. During flight testing it would be desirable to monitor the tail rotor shaft torque.

For hover, K_{HOV} is determined by using the rotor thrust coefficent whereas for cruise calculations the rotor lift coefficient (C_T') is used. Note, it is presented that generic equations are developed for the determination of both hover and cruise powers required. This approach results in K_1 factors for hover identical to unity, with the correction factor from theory-to-test absorbed within the K_{HOV} term. The approach includes ground effects. Note, the induced power correction term determined in Equation (13) is used in both equations for determining hover and cruise powers required. However, only the K_{HOV} terms calculated for out-of-ground-effect conditions are used in the cruise equations.

Using the test data acquired for hover at various helicopter heights above ground level (skid height represented by h_{skid}), values of K_{HOV} are determined as a function of thrust coefficient and skid height. This is mathematically represented below as:

$$K_{HOV} = \sum_{i=0}^{n1} \left[\sum_{j=0}^{n2} \left[\sum_{k=0}^{n3} (C_{ijk_{HOV}}) * (C_T)^i * (\, h_{skid} \,)^j * (\, N_R \,)^k \right]\right] \tag{15}$$

where

n1 is the order of C_T

n2 is the order of h_{skid}

n3 = order of N_R

$C_{ijk_{HOV}}$ are the coefficients of the polynomial which defines K_{HOV}.

With K_{HOV} established it is now possible to calculate the induced power required.

Defining the non-dimensionalized forward flight advance ratio as:

$$\mu'_{MR} = [\, \mu^2_{MR} - \bar{v}_{i_{MR}}{}^2 \,]^{1/2} \tag{16}$$

the induced power coefficient equals

$$C_{P_{IND_{MR}}} = \frac{K_{IND_{MR}} * C_{T_{MR}}'^{2}}{2\mu'_{MR}} \tag{17}$$

The parasite power efficiency term K_{PER} is derived from flight test data. The parasite power coefficient is calculated from

$$C_{P_{PAR_{MR}}} = \mu_{MR} * C_{X_{MR}} * K_{PER_{MR}} \tag{18}$$

For the given flight conditions under examination K_{NUD} is determined from an experimentally derived database.

The non-uniform downwash power coefficient is calculated from:

$$C_{P_{NUD_{MR}}} = \frac{2.0 * K_{NUD_{MR}} * C_{T_{MR}}' * \sigma_{MR}}{B^2_{MR}(\, 1 + D_{L_{wing}} * \sin^2 \varepsilon \,)} = \frac{2.0 * K_{NUD_{MR}} * C_L * \sigma_{MR}}{B^2_{MR}} \tag{19}$$

3.3.2. Tail Rotor Power Required

The previous section defined the set of equations for determining the power required of the main rotor system. In order to determine the tail rotor power required, the same set of equations must be re-entered but with corresponding values for tail rotor replacing the main rotor. Therefore, the subscripts TR and VT would be substituted everyplace where MR and WING, respectively exists. This accounts for the tail rotor and vertical tail contributions.

The tail rotor produces anti-torque by generating a resultant thrust vector at some moment arm distance to create a moment force equal and opposite to the torque generated by the main rotor. The approach used for consideration of the vertical fin aerodynamics is similar to the wing aerodynamics for unloading the main rotor lift. Therefore, the tail rotor thrust is considered as a lift force. Also, the tail rotor is assumed to produce zero propulsive force resulting in zero contribution for parasite power. Programmatically this is accomplished by setting the total flat plate effective drag (Fe) to zero.

Setting the thrust requirement (lift) of the tail rotor as a function of the main rotor torque and moment arm results in

$$L_0 = \frac{Q_{MR}}{l_{TR}} = \frac{HP_{MR} * 550}{\Omega_{MR} * l_{TR}} = \frac{550 * HP_{MR} * R_{MR}}{V_{T_{MR}} * l_{tr}} \tag{20}$$

where Q_{MR} is the mair rotor torque required and l_{TR} is the arm between the main rotor and tail rotor axes. Non-dimensionalizing the lift term results in

$$C_{L0} = \frac{C_{P_{MR}} * R_{MR}}{l_{TR}} * \frac{(A_{MR} * V_{T_{MR}}^2)}{(A_{TR} * V_{T_{TR}}^2)} \tag{21}$$

Additional changes to the main rotor inputs for assessing the tail rotor include setting the $C_{L_{wing}}$ equal to the vertical fin C_L, the A_{wing} equal to the vertical fin area, and the $D_{L_{wing}}$ equal to the download (blockage force) of the vertical fin.

The presence of the vertical fin in connection with the tail rotor produces a blockage. Tail rotors can be classified as "pusher" types where their thrust pushes against the vertical fin or "tractor" types where the vertical fin is on the slipstream side of the tail rotor. The effect of the vertical fin is somewhat different for pusher and tractor tail rotor systems. However, while this difference is not considered in the presented methodology a simplified approach to include vertical fin blockage is included as a download. This results in an effective tail rotor thrust-to-sideforce requirement necessary for anti-torque.

3.3.3. Total Level Flight Power Required

The above procedure is conducted for the flight conditions tested and presented in the U.S. Army's flight test substantiation data reports. As discussed previously, the equation and algorithm development for hover and forward flight operation conditions have been developed to be as generic as feasible. However, certain differences do exist.

For hover flight conditions, K_1 is identically equal to unity. An intermediate calculation in determining the power required for hover IGE regards the calculation of K_{HOV} which is a function of thrust coefficient, rotor RPM, and operating skid height. Hover IGE is defined as when the desired operating skid height is less than the input OGE skid height. All operating skid height values equal to or greater than the input OGE value are evaluated at the OGE input skid height.

Note, because of the sparsity of test data available for a range of skid heights the calculated polynomials for K_{HOV} may result in erroneous powers required in the range between the last IGE skid height data point and the OGE input height value. The hover OGE powers required are known to exceed the IGE values for the same operating conditions. Therefore, all IGE powers required must be compared against and limited by the equivalent OGE powers required.

In forward flight, a matrix of K_1's are determined as a function of advance ratio (μ), thrust (C_T), operating rotor speed (N_R), and power for an individual helicopter configuration. A comprehensive matrix equation solver is now employed to permit determination of the coefficients which describe K_1 in terms of μ, C_T, N_R.

Hence, the values of K_1 are determined from

$$K_1 = \sum_{i=0}^{n1} \left[\sum_{j=0}^{n2} \left[\sum_{k=0}^{n3} (C_{ijk_{PWRQ}}) * (C_T)^i * (\mu)^j * (N_R)^k \right] \right] \tag{22}$$

where

n1 = order of C_T
n2 = order of μ
n3 = order of N_R
$C_{ijk_{PWRQ}}$ are the coefficients of the polynomial which defines the K_1's which are inserted in equation (6).

Once the power required for the aircraft in level 1 "g" flight is determined, the powers required associated with climb rates and accessory power losses are directly added.

3.3.4. Power Available

To minimize computer space and runtime, CHIMP is provided with only one power available option. However, APECOMP provides three options for assessing the total engine powers available and include Direct Power Available, Referred Format, and Turbine Outlet Temperature vs. Torque Relationship. Depending on the engine type and data available an engine option is selected within APECOMP and then downloaded into CHIMP. The total engine power available for specified operating conditions is determined as a function of single and dual engine operating limits. Inclusion of accessory power extraction (losses) such as anti-ice, bleed air, scavenge, and electrical load are accounted for by increasing the power required instead of decreasing the power available. This is due to the fuel flow equations which are a function of power required.

3.3.4.1. Direct Power Available

This options utilizes the absolute values of input power available as acquired during flight testing.

While the primary advantage of this methodology is its high fidelity in predicting the input data, its biggest disadvantage lies in the inability to predict powers available at TITs different from the input data.

An equation for power available is developed as a function of ambient temperature and Pressure Altitude (PA) for each input power rating. This yields

$$(SHP_{avail}) = \sum_{i=0}^{n1} \left[\sum_{j=0}^{n2} (C_{HPavail_{ij}}) * (FAT)^i * (PA)^j \right] \quad (23)$$

n1 = order of Free Air Temperature
n2 = order of Pressure Altitude
$C_{ij_{avail}}$ are the coefficients of the polynomial

Because of the potential for large errors, no curvefit capabilities are provided between the minimum and maximum input engine ratings.

3.3.4.2. Referred Format

This option non-dimensionalizes the absolute engine power available data as a function of referred Turbine Inlet Temperature (TIT), ambient pressure ratio, and ambient temperature ratio. Note, corresponding fuel flow can also be referred. There exists three primary advantages of this approach:

- Resulting compact set of equations
- Ability to determine power available at TIT's different from the engine operating ratings
- Predictive capability to upgrade engine power available

Before equations are developed for determining referred powers available, the following non-dimensionalized conversions are conducted:

$$(SHP_{ref}) = \frac{SHP}{(SHP^* * (\theta)^i * (\delta)^j)} \quad (24)$$

where

(SHP^*) = Maximum Static Sea Level Installed Horsepower Rating

θ = Ambient Temperature (°K) divided by Temperature at Sea Level Standard (°K)

δ = Ambient Pressure divided by Pressure at Sea Level Standard

the superscripts (i) and (j) are user-defined and are generally equal to 0.5 and unity, respectively

The TIT is referred according to

$$(T_{4.1_{ref}}) = \frac{T_{4.1}}{(\theta)^i} \quad (25)$$

An equation for referred power available is now developed as a function of referred TIT ($T_{4.1ref}$) and Pressure Altitude (PA) yielding:

$$(SHP_{ref_{avail}}) = \sum_{i=0}^{n1} \left[\sum_{j=0}^{n2} (C_{HPref\text{-}av_{ij}}) * (T_{4.1_{ref}})^i * (PA)^j \right] \quad (26)$$

n1 = order of $T_{4.1_{ref}}$
n2 = order of PA
$C_{HPref\text{-}av_{ij}}$ are the coefficients of the polynomial

The referred values are then converted back to absolute powers available.

3.3.5. Turbine Outlet Temperature vs. Torque Relationship

This approach is based upon typical power assurance checks provided in the flight (operator's) manual. The determination of power available includes Turbine Outlet Temperature (TOT) and ambient Pressure Altitude (PA) and Free Air Temperature (FAT). This approach permits determination of power available for performance calculations or a power check typical of pilot operations. A two-step procedure is used with the first intermediate step determining a dummy variable as a function of TOT and ambient temperature. The second step determines power available as a function of the dummy variable and the altitude.

$$dummy = \sum_{i=0}^{n1} \sum_{j=0}^{n2} C_{PAV1_{ij}} * (TOT)^i * (FAT)^j \quad (27)$$

where

n1 = order of TOT
n2 = order of FAT

The "dummy" variable is passed to the second step of the procedure to calculate power available as follows:

$$C_{Q_{AVAILABLE}} = \sum_{i=0}^{n1} \sum_{j=0}^{n2} C_{PAV2_{ij}} * (dummy)^i * (PA)^j \quad (28)$$

where

n1 = order of dummy
n2 = order of PA

$$SHP_{avail} = \frac{(RHP_{xmsn})}{(\eta_{xmsn})} + (\Delta HP_{acc}) \quad (29)$$

where

RHP_{xmsn} is the power available at the main gearbox rotor shaft

η_{xmsn} is the mechanical efficiency of the main gearbox

ΔHP_{acc} is a user-defined constant.

3.4. Fuel Flow

As presented in the power available discussion, an option for determining fuel flow is selected in APECOMP and then downloaded into CHIMP. The two fuel flow options are based upon using either absolute or referred values. However, flight and ground idle fuel flow calculations are independently provided solely as a function of absolute input values.

3.4.1. Direct Fuel Flow

This options utilizes the absolute values of input fuel flow as a function of operating engine power. Based on the considerable data typically provided in the AVSCOM digital database, this option is recommended for its high fidelity solutions.

An equation for absolute values of fuel flow is developed as a function of input power (required SHP), FAT, and PA which yields:

$$W_{FF}=\sum_{i=0}^{n1}\left[\sum_{j=0}^{n2}\left[\sum_{k=0}^{n3} C_{ijk} * (PA)^{i} * (FAT)^{j} * (SHP_{req})^{k}\right]\right] \tag{30}$$

n1 = order of Pressure Altitude
n2 = order of Free Air Temperature
n3 = order of required SHP
C_{ijk} are the coefficients of the polynomial

3.4.2. Referred Fuel Flow

Before equations are developed for determining referred fuel flow available, the following non-dimensionalized conversions are conducted:

$$W_{FF_{ref}}=\frac{W_{FF}}{SHP^{*} * (\theta)^{i} * (\delta)^{j}} \tag{31}$$

where

SHP^{*} = Maximum Static Sea Level Installed Horsepower Rating

θ = Ambient Temperature (°K) divided by Temperature at Sea Level Standard (°K)

δ = Ambient Pressure divided by Pressure at Sea Level Standard

W_{ff} = Fuel flow in pounds per hour

the superscripts (i) and (j) are user-defined and are generally equal to 0.5 and unity, respectively

The SHP corresponding to the fuel flows are referred in the same manner as presented for referred powers available. Now a direct correlation between referred fuel flow and referred SHP exists. Once the values of referred fuel flow are obtained they are then converted back to absolute fuel flows.

4. Integrated Mission Planner

The methodology described herein is applicable to any helicopter mission planning and performance system. A single set of software modules can be incorporated into ground-based, on-board, or portable computer systems. Since the primary development objective of CHIMP is to run on handheld computer systems the following sections describe the hardward and software environment.

5. Hardware Description

CHIMP software is written for execution on a variety of IBM-compatible computer platforms and various "palmtop" computers. The Hewlett-Packard 95LX palmtop computer is selected as the platform of choice due to its rugged construction, supportability, compact size, low weight, software compatibility, and affordability. The HP-95LX provides the functionality of a standard desktop Personal Computer in a package which weighs less than one pound and fits into a flight suit pocket. An expansion bus connector is provided which allows peripherals to be connected via interface cable. The bus provides for interconnection between the HP-95LX and other external computer systems, ground-based mission planners, or on-board mission processors. The screen is a super-twist liquid crystal display (LCD) which displays 16 lines of 40 columns each. The internal RAM capability of 1.0Mb and credit card-size memory cards are used for data transfer and storage. These memory cards and the LCD display have a low power consumption yielding a long battery life (2 AA size required).

6. Software Description

6.1. Introduction

CHIMP consists of four modules which include a File Manager and three separate computer programs. The three computer programs can be operated independently or as an integrated system. The four modules which constitute CHIMP are:

- Module 1 - File Manager
- Module 2 - Navigation
- Module 3 - Weight&Balance
- Module 4 - Performance

6.2. File Manager

CHIMP allows the user to open and save new or existing Navigation, Performance, and Weight & Balance files to be used separately or merged into a single integrated file providing connectivity between the all modules. This allows for the sharing of common data, reducing program size, data storage, and user error. This results in a truly "integrated" mission planning system. The Navigation and Performance modules use a single structure, allowing them to "share" common mission leg data. The distance and time between any two check points in the navigation module are treated as cruise leg data in the performance module. The cumulative distance and time associated with the mission check points as well as the pressure altitude, free air temperature, true air speed, and indicated air speed are all common to the performance and navigation modules.

Weights data and associated item incremental drag originating from the Weight & Balance module (i.e. weights listed on a weight computation card) can be passed to the Performance module for use in the mission performance calculations. The weight of the fuel burned during the mission, the payload weight, and drag associated with a dropped or added item are passed back to the weight and balance module. The dropped or added fuel and payload are used to calculate the landing weight.

6.3. Navigation

6.3.1. Introduction

The Navigation module is a navigational aid integrated with mission performance which allows the user to compute latitude, longitude, distance, course, wind speed, wind direction, ground speed, heading, and time for given input parameters.

6.3.2. Spheroid Calculations

The Earth is not a sphere, but an ellipsoid or spheroid, flattened slightly at the poles and bulging somewhat at the Equator. The spheroid methodology is used as a surface of reference for the mathematical reduction of geodetic and cartographic data.

Rhumbline and Great Circle routines used to calculate distance/course and Latitude/Longitude are based on Spheroid calculations. CHIMP provides the user with several spheroid model choices. Each of the various spheroid models has associated with it an equatorial radius and a flattening factor. Each spheroid is best used in a certain part of the world. Where it is actually used for calculation purposes can either be automatically determined by CHIMP or user selected. The Spheroids implemented into CHIMP provide world-wide coverage.

The default spheriod model used in the CHIMP navigation calculations is the WGS-84 spheroid. The WGS is not referenced to a single datum point. It represents an ellipsoid or spheroid whose placement, orientation, and dimensions best fit the earth's equipotential surface which coincides with the geoid (the actual earth). The system was developed from a worldwide distribution of terrestrial gravity measurements and geodetic satellite observations. The goal of the DMA (Defense Mapping Agency) is to eventually refer all positions on the earth to the World Geodetic System (WGS), which has a specific set of defining parameters which will most accurately represent the world.

CHIMP's Navigation module can printout all data in a variety of formats to accommodate the specific user group's needs. For example, Time-Distance-Heading cards can be printed out in large type for NVG use or can be formatted knee board size.

6.4. Weight & Balance

The Weight & Balance Module of CHIMP is based upon the Military standard weight and balance charts and forms such as DD Form 365F and Mil Std 1374. The module contains sufficient instruction and data so that an aviator, knowing the aircraft's tail number, can compute the safe flight weight and balance of the aircraft for any mission configuration. To adequately determine the total weight and balance information for the aircraft it is necessary to compute longitudinal and lateral centers of gravity as generally required on DD Form 365F. The center of gravity limitation charts are duplicated in the Weight & Balance module and automatically calculate aircraft CG at a given takeoff weight. Generally, longitudinal computations will include all items installed on the aircraft, while lateral computations will include only those items which cause lateral imbalance when mounted or carried on the aircraft. The weight and balance module of CHIMP allows inclusions of any or all items in longitudinal or lateral computations.

The aircraft takeoff weight is built up by specifying quantity numbers of individual items in various default or user defined databases or groups including: Fuel System, Armament, Ordnance, Special Equipment, Corrections and Fuel. New groups or item names can be added if desired. When entering a new item name, the quantity, weight and station line or moment must also be entered as well as any limits and defaults for this information.

Limits for all inputs in item and group levels are used to check input parameters. Defaults for all inputs can also be entered. Both Station line and Butt line calculations are computed automatically. A running total of Takeoff Weight and CG location is displayed. Incremental drag associated with each item can also be input. If any item is dropped or added during the mission profile the corresponding drag for that item will also be dropped or added.

CHIMP can create a library of data files compatible with typical military pre-flight planning specific to the service requirements. Standard aircraft configuration files have been developed for several military aircraft. These standard configurations can be pulled into the Weight & Balance module from an external file by specifying the aircraft tail number. Associated with the aircraft tail number will be that particular aircraft configuration, the aircraft basic weight and longitudinal and lateral moment.

CHIMP can printout all weights data in a variety of formats to include DD Form 365F, Mil Std 1374, and other weight card formats.

6.5. Performance

6.5.1. Introduction

CHIMP's helicopter performance methodology is based upon the analytical techniques presented herein. Without the development of APECOMP, CHIMP could not run on palmtop computer systems.

6.5.2. Mission Profile

Mission profiles can be user selected or can be imported from the Navigation module. Also, pre-defined missions can be stored and recalled regardless of aircraft type. For example, the profile developed for a troop transport mission can be used by the escort gunships. All mission profiles are developed from mission legs which are user selectable and include:

- Idle (Flight, Ground)
- Takeoff, Hover, Land
- Climb (V_X, V_Y, V_{ROC}, etc.)
- Cruise (V_{KTAS}, V_{KIAS}, HP&XMSN limits, V_{BR}, etc.)
- Transfer Altitude, Payload, Fuel
- Descent
- Loiter
- Reserve Fuel

CHIMP can determine mission performance tradeoff studies. For example, payload versus radius trades can be conducted for takeoff critical conditions. Conversely, for Combat Search and Rescue missions the trade studies can be conducted with the mid-mission hover point as the critical (limiting) flight condition.

Also, for time critical missions, the user can define the required time at the Landing Zone and work the mission backwards to establish a Takeoff Time. Trades can be conducted on prevailing winds, indicating the change in Indicated Airspeed required to meet "hard leg times" for given perturbations in wind. Another CHIMP feature examines excess performance margins. For example, when an escort gunship is diverted from the fleet and desires to re-group, CHIMP determines if the aircraft has ample delta cruise airspeed from the troop helicopters to catch-up within the required hard times either at each waypoint, final approach fix, or LZ.

6.5.3. Data Output

CHIMP has been developed with the flexibility to adapt to any user defined printout. Typical printout formats include USA PPC, USN Computation Cards, Mission Summary, Flight Plan (DD 175), Helo Log, Special Mission Planning Card, Aircrew Mission Briefing, and many others.

7. Conclusions

Advances in computer hardware, software, and mathematical techniques have been successfully incorporated into a "palmtop" mission planning and performance system. The Computerized Handheld Integrated Mission Planner (CHIMP) offers a low cost, low weight, NDI system for military helicopters which greatly reduces pilot's pre-flight time and can be carried on board for use in austere operations or during amended clearances. CHIMP provides efficient computations, significantly reduced database storage requirements, and high fidelity, i.e., CHIMP has been validated for several military helicopters to be within one percent of flight manual data. The successful development of CHIMP is made possible from use of the smooth and continuous semi-empirical algorithms presented herein for predicting helicopter operating capabilities and limitations. These algorithms reduces the database size of current techniques by a factor of ten while increasing computational speed to permit real-time operations with low-cost processors. CHIMP's common software architecture and communications capabilities permit data transfer between other ground-based or on-board mission planning systems. Other salient features include single system for all single and tandem rotor helicopters, real-time calculations, integrated weight & balance and navigation with mission performance, flight performance extrapolation, Jeppeson-Sanderson NAVAID compatibility, portable software, and expandability (electronic flight manual, contour flight, NOE).

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