NINTH EUROPEAN ROTORCRAFT FORUM

PAPER NO. 24

SOVIET AND U.S. WEIGHT-PREDICTION METHODS AS TOOLS IN HELICOPTER OPTIMIZATION

W. Z. STEPNIEWSKI
Aeronautical Consultant
Springfield, Pa. USA

and

R. A. SHINN
U.S. Army AVRADCOM
St. Louis, Mo. USA

September 13–15, 1983

STRESA, ITALY

Associazione Industrie Aerospaziali

Associazione Italiana di Aeronautica ed Astronautica

ABSTRACT

One Soviet and two U.S. weight-prediction methods are compared regarding their suitability in determining values of design parameters (disc loading, tip speed, and number of blades) which would minimize the summary weight of the following major helicopter components: blades, hubs and hinges, fuselage, drive system, and flight controls. This is done by examining the influence of varying the design-parameter values on ratios relating first, individual component weights and then, their summary weights, to the corresponding weights of a baseline helicopter. Considerable differences were found in all three methods; especially, in Soviet vs. U.S., regarding the "design-parameter-variation — weight-ratio" relationships for blades and hubs plus hinges. However, agreement was much closer in the case of fuselage and flight controls, and almost perfect for drive systems. As to the summary weight, both of the U.S. methods point toward a sharp, constrained minimum at a disc-loading of 12 psf, tip speed of 720 fps, and 6 blades; while the Soviet approach shows a shallow, unconstrained optimum at a disc-loading of about 9.5 psf; however, as in the U.S. case, tip speed and number of blades remain at their maximum permissible values of 720 fps and 6 blades, respectively.

LIST OF SYMBOLS

AR	aspect ratio
a	adjustment factor; also design coefficient
CF	centrifugal force; m.ton
c	blade chord; ft or m
D	diameter; ft
F	factor
FF	fuel flow
k	direct weight coefficient
k^*	indirect weight coefficient
k_{ai}	air-duct specific weight; psf
L	distance between rotors; ft or m
L_c	cabin length from nose to end of cabin floor, ft
L_{dr}	horizontal distance between main-rotor hubs (main-to-tail); ft
L_{rw}	ramp-well length; ft
M	moment or torque; ft-lb or kg-m
n	number
n_{ult}	ultimate load factor
R	rotor radius; ft or m
$\overline{R}$	$\overline{R} \equiv R/16m$
r	radius of blade attachment fittings; ft
S	area; ft^2 or m^2
SHP	shaft horsepower; hp or cv
sw	specific weight; psf
T	power-to-rpm ratio
t	blade thickness at 25% R; ft
V	flight velocity; kn
V_t	tip speed; fps or m/s
W	weight; lb or kg
w	disc loading; psf
z	number of stages in main-rotor drive
α_λ	blade-type coefficient
α_Q	nonuniform torque coefficient
ΔCG	center-of-gravity range; ft
λ	blade aspect ratio
$\overline{\lambda}$	$\overline{\lambda} \equiv \lambda/18$
λ_o	$\lambda_o = 20/\overline{R}$ (steel) or $\lambda_o = 12.4/\overline{R}$ (aluminum)
ν_1	first natural blade frequency in flap bending; per rev.
σ	rotor solidity

Subscripts

b	baseline
bl	blade
ds	drive system
f	fuselage
fc	flight controls
h	hubs and hinges

Superscripts

$-$	ratio to corresponding item in baseline helicopter
$\sim$	ratio to design gross weight of baseline helicopter

SOVIET AND U.S. WEIGHT-PREDICTION METHODS
AS TOOLS IN HELICOPTER OPTIMIZATION

by

W. Z. Stepniewski
Aeronautical Consultant
Springfield, Pa. USA

R. A. Shinn
U.S. Army AVRADCOM
St. Louis, Mo. USA

1. INTRODUCTION

In the concept formulation and preliminary design phases of rotary-wing aircraft, two important contributions provided by the weight discipline are: (1) close estimation of the weights of major components even though only sketchy information regarding technical details may be available at the time, and (2) selection of design parameter values which would minimize the structural weight of the aircraft or, at least, establish a general trend as to the influence of the design parameter variations on changes in the weights of various major components.

The first of these aspects was considered by the authors in a paper presented at the AHS 39th Annual Forum in May 1983[1], and a more elaborate comparative study[2] where weight-prediction methods (one Soviet, as represented by Tishchenko et al[3], and two U.S., one by Boeing Vertol[4] and another by the U.S. Army Research and Technology Labs[5]) were examined by comparing estimated component weights with actual weights of both Soviet and Western helicopters.

As a follow-up to the above-mentioned works, the second aspect of the weight discipline contribution to the concept formulation and preliminary design phases of helicopters is examined here. This is accomplished in the following way:

Using one Soviet and the two U.S. weight-prediction methods discussed in Refs. 1 and 2, the trends indicated by each method will be established regarding the influence of three design parameter variations (disc loading, tip speed and number of blades) on the weights of the following major components: main-rotor blades, hubs and hinges, fuselage group, drive system, and flight-control group. Following this, a combination of design parameter values which would minimize the summary weight of the five major helicopter components will be sought.

The procedure used in both these tasks is based on relating parameter and component weight values to the corresponding values of a baseline helicopter. This approach may be quite attractive in design-optimization practice, as weights of the baseline machine may be determined either by detailed calculations or simply, pre-established, as would be the case should the baseline machine be an already existing aircraft. Consequently, if a reliable method showing how relative weights change as design parameters deviate from their baseline values could be established, then a confidence-inspiring procedure for finding a combination of design-parameter values leading to the minimal weight could be developed. To test this approach, the 30,000-pound gross-weight transport helicopter discussed in the AHS/HAI Commercial Users Design Conference[6] was selected as a reference or focal point, Next, the influence of parametric variations on the weights of the major components of modified helicopters was determined, and the new modified weights were compared to those of the baseline machine.

In the studies reported in Ref. 6, the design gross weight of the helicopter was assumed constant, while the installed power varied as a result of meeting various performance and operational requirements.

But in this paper, both design gross weight and installed power will be assumed constant in order to simplify the problem. It should also be emphasized that the C_T/σ value remains constant throughout all changes in the values of the design parameters. This obviously, would force variation in the blade chord length as the selected design parameters vary.

With respect to the major components considered here, it should be noted that their number is limited to five. The four additional components which were discussed in Refs. 1 and 2 (tail-rotor group, landing gear, fuel system, and propulsion subsystem) are excluded since, under the assumptions of constant design gross weight and constant power installed, the last three would not be affected by variations of the selected design parameters. Although the weight of the tail-rotor group may experience some changes with variation of the tip speed and disc loading, the influence of those changes on the overall weight-minimization process would be negligible since the tail-rotor group usually contributes less than one percent to the design gross weight of a helicopter (see Table 3.4[2]).

Using formulas presented in Soviet and U.S. weight-prediction methods [Eqs. (1) through (5b)], a computer program was written to calculate the weights of the five major components as the values of design parameters vary from their baseline level.

The results of these calculations are graphically represented as ratios of the major component weights of the modified helicopters to those of the baseline machine. In addition, analytical expressions for the weight ratios are also given. In this way, general trends regarding the influence of the design parameter variations on weights of each of the five major components can be shown as anticipated by the three compared methods. Combining these individual trends into ratios of the summary weights of the five major components to the corresponding weights of the baseline helicopter, one would be able to ascertain how each of the compared methods forecasts a set of design parameter values that would minimize the summary weight. In this way, the base necessary for discussion of similarities and differences for each of the three compared methods can be established; thus enabling evaluation of their usefulness as a tool in the helicopter structural-weight minimization process.

2. WEIGHT-PREDICTION FORMULAS

Weight-prediction formulas representing the three methods considered in this paper were discussed in greater detail in Refs. 1 and 2; consequently, only those related to the five major components are reproduced here in order to give the reader some idea as to their structure, as well as some indication of the various inputs required in the weight-prediction process.

The weight-prediction formulas for main-rotor blades are Eq. (1) as given by Tishchenko, Eq. (1a) as given by Boeing Vertol, and (1b) as given by the U.S. Army Research & Technology Labs.

$$n_{bl}W_{bl} = k^*_{bl}(\sigma R^{2.7}/\bar{\lambda}^{0.7})[1 + \alpha_\lambda \bar{\bar{R}}(\lambda - \lambda_o)] \tag{1}$$

$$n_{bl}W_{bl} = 44a[(10^{-4}W_{gr}n_{lf})(0.01R^2)0.1(R - r)n_{bl}ck_r(R^{1.6}/k_d t)]^{0.438} \tag{1a}$$

$$n_{bl}W_{bl} = 0.02638n_{bl}^{0.6826}c^{0.9952}R^{1.3507}V_t^{0.6563}\nu_1^{2.5231} \tag{1b}$$

Weight-prediction formulas for main-rotor hubs and hinges are shown below in the same order as in the preceding section.

$$W_h = k^*_h k_{n_{bl}} n_{bl}(CF)^{1.35} \tag{2}$$

$$W_h = 61a[W_{bl}R_{mr}(rpm)^2_{mr}(HP_{mr})r^{1.82}n_{bl}^{2.5}k_{mad}10^{-11}]^{0.358} \tag{2a}$$

$$W_h = 0.002116n_{bl}^{0.2965}R_{mr}^{1.5717}V_t^{0.5217}\nu_1^{1.9550}(n_{bl}W_{bl})^{0.5292} \tag{2b}$$

Formulas for predicting fuselage group weights are summarized below. It can be seen from Eqs. (3) through (3b) that the Tishchenko approach is much simpler than those of either Boeing Vertol or RTL. A single term is used in Eq (3); while in Western methods, the weights of several subassemblies are computed separately.

$$W_f = k^*_f W_{gr}^{0.25} S_v^{0.88} L^{0.16(1+a)} \tag{3}$$

$$W_f = 125a\left\{[(10^{-4} W_{gr})n_{ult}(10^{-3} S_f)(L_c + L_{rw} + \Delta CG)]^{0.5} \log V_{max}\right\}^{0.8} + S_{ht}(sw)_{ht} + n_{eng}(W_{eng} n_{clf})^{0.41} + n_{eng} S_n k_n + n_{eng} D_{eng} L_{ad} k_{ai} \tag{3a}$$

$$W_f = 10.13(10^{-3} W_{gr_{max}})^{0.5719} n_{ult}^{0.2238} L^{0.5558} S_f^{0.1534} I_{ramp}^{0.5242} + 0.7176 S_{ht}^{1.1881} AR_{ht}^{0.3172} + 1.0460 S_{vt}^{0.9441} AR_{vt}^{0.5332} n_{gtr}^{0.7058} + 0.2315 S_{nw}^{1.3476} + 0.0412 W_{eng}^{1.1432} n_{eng}^{1.3762} \tag{3b}$$

Looking at Eqs. (4) through (4b), it is interesting to note that each of the compared methods represents a somewhat different philosophy in estimating drive-system weights. Tishchenko breaks down the whole process into separate weight estimates of main gearboxes, intermediate gearboxes, tail-rotor gearboxes, and transmission shafts. Boeing Vertol (at least for single-rotor helicopters) separately computes the weights of the main-rotor and tail-rotor drive systems; while in the RTL approach, the weights of all gearboxes and drive shafts are calculated.

$$W_{ds} = k^*_{mgb} n_{mgb} (\alpha_Q M_{av})^{0.8} + k^*_{igb} n_{igb} (\alpha_Q M_{eq})^{0.8} + k^*_{trgb} M_{tr}^{0.8} + k_{sh} L_{sh} M_{ult}^{2/3} \tag{4}$$

$$W_{ds} = 250 a_{mr} [(HP_{mr}/rpm_{mr}) z_{mr}^{0.25} k_t]^{0.67} + 300 a_{tr} [1.1(HP_{tr}/rpm_{tr})]^{0.8} \tag{4a}$$

$$W_{ds} = 172.7 T_{mrgb}^{0.7693} T_{trgb}^{0.079} n_{gb}^{0.1406} + 1.152 T_{mrgb}^{0.4265} T_{trgb}^{0.0709} L_{dr}^{0.8829} n_{dsh}^{0.3449} \tag{4b}$$

Expressions representing the three compared methods for predicting weights of the flight-control group are given in Eqs. (5) through (5b).

$$W_{fc} = k_{bc} n_{bl} c^2 R + k_{mc} R \tag{5}$$

$$W_{fc} = k_{cc}(10^{-3} W_{gr})^{0.41} + k_{mrc}[c(R n_{bl} W_{bl} 10^{-3})^{0.5}]^{1.1} + k_{rsc}(10^{-3} W_{pmr})^{0.84} \tag{5a}$$

$$W_{fc} = 0.0985(F_{cp})^{0.3368}(W_{gr})_{max}^{0.7452}/(F_{cb})^{1.1125} + 0.1657(F_{cb})^{1.3696} c^{0.4481} F_{cp}^{0.4469}(W_{gr})_{max}^{0.6865} \tag{5b}$$

3. BASELINE HELICOPTER

3.1 Characteristics

The general arrangement of the baseline helicopter shown in Fig. 1, as well as some of the information needed for major component weight predictions was directly obtained from Ref. 6. This was supplemented by inputs from Refs. 7 and 8, and personal discussions with Messrs. S. Mills and C. Fay (authors of Refs. 7 and 8). As a result of these inputs, the values of the various items characterizing the baseline helicopter are shown in Table 1, where figures directly obtained from Refs. 6, 7, and 8 are shown in brackets, while those assumed by the authors are without brackets.

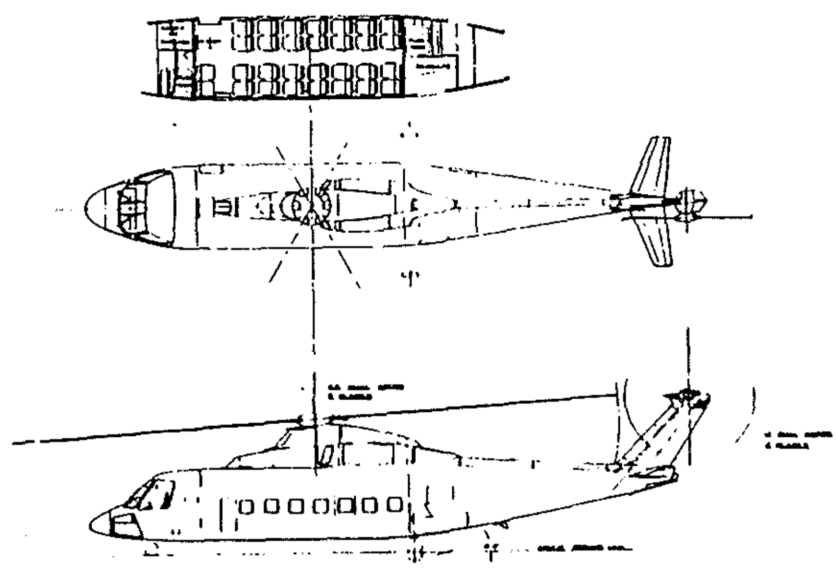

Figure 1. General arrangement of the baseline helicopter[6]

TABLE 1

KNOWN AND ASSUMED PARAMETER VALUES FOR THE BASELINE HELICOPTER

PARAMETER	VALUE
DESIGN GROSS WEIGHT: lb	[30,000]
DES. MANEUVER LOAD FACTOR, g	2.75
MAX. FLYING GROSS WEIGHT, lb	36,000
MAIN-ROTOR TYPE	[Articulated]
MAIN-ROTOR RADIUS, ft	[33.0]
MAIN-ROTOR DISC LOADING, psf	[8.77]
MAIN-ROTOR No. OF BLADES	5
MAIN-ROTOR BLADE CHORD, ft	2.22
M.R. BLADE THICKNESS AT R = 0.25 ft	0.22
M.R. TIP SPEED, fps	[670.0]
M.R. ANGULAR VELOCITY: rpm	[193.9]
M.R. BLADE FIRST NAT. FREQ/REV.	1.03
M.R. BLADE ATTACHMENT RAD: ft	2.10
INSTALLED POWER: hp	6200
M.R. HUB MATERIAL	Titanium
M.R. HUB DEVELOPMENT STAGE	Early
TAIL-ROTOR BLADE RADIUS, ft	7.25
TAIL-ROTOR BLADE CHORD: ft	1.02
TAIL-ROTOR No. OF BLADES	4
T.R. BLADE ATTACHMENT RAD. ft	0.98
T.R. HORSEPOWER: hp	620
T.R. TIP SPEED, fps	670
T.R. RPM	882
DIST. BETWEEN ROTOR AXES, ft	40.92
FUSELAGE LENGTH, ft	64.02

PARAMETER	VALUE
CABIN LENGTH: ft	42.9
ULTIMATE LOAD FACTOR, g	4.125
C.G. RANGE: ft	1.0
MAX. FLYING SPEED, kn	[165.0]
HORIZONTAL TAIL AREA, ft^2	38.4
HORIZONTAL TAIL AR	5.0
VERTICAL TAIL AREA, ft^2	32.0
VERTICAL TAIL AR	2.0
EMPENNAGE SPECIFIC WT., psf	1.3
NUMBER OF ENGINES	2
ENGINE WEIGHT: lb	700.0
CRASH LOAD FACTOR, g	12
NACELLE AREA: ft^2	38.0
SPECIFIC WT. OF COWLINGS, psf	1.0
ENGINE DIAMETER, ft	2.5
LENGTH OF AIR DUCT, ft	2.3
No. OF TAIL ROTOR GEARBOXES	2
No. OF MAIN GEARBOXES	[1]
No. OF MAIN GEARBOX STAGES	3
No. OF INTERMEDIATE GEARBOXES	1
TOTAL NUMBER OF GEARBOXES	3
LENGTH OF DRIVESHAFTS, ft	33.0
MAIN-ROTOR HORSEPOWER, hp	4680
FUSELAGE WETTED AREA, ft^2	1645
TYPE OF CONTROL	[Boosted]

3.2 Weights of the Five Major Components

Using Eqs. (1) through (5b) and data from Table 1, the weights of the five major components of the baseline helicopter were computed, and the results presented in Table 2 as ratios of the component weight to the helicopter design gross weight. The fraction (ϵ) of the component weight, which remains invariant as the design parameters deviate from their baseline level, are also indicated. Statistical average values for the Western single-rotor helicopters examined in Ref. 2 are also shown in this table.

TABLE 2

RELATIVE MAJOR COMPONENT WEIGHTS

COMPONENT	RELATIVE COMPONENT WEIGHTS AND THEIR INVARIANT FRACTIONS (ϵ)						STATISTICAL AVERAGES FROM REF. 2*
	TISHCHENKO		BOEING VERTOL		RTL		
	REL. WT	ϵ	REL. WT.	ϵ	REL. WT.	ϵ	
MAIN-ROTOR BLADES	0.063	0	0.049	0	0.051	0	0.056[a]
M.R. HUBS & HINGES	0.067	0	0.031	0	0.042	0	0.049[b]
FUSELAGE	0.128	0	0.124	0.10	0.124	0.19	0.139[c]
DRIVE SYSTEM	0.098	0.16	0.077	0.08	0.091	0.07	0.106[d]
FLIGHT CONTROLS	0.041	$\kappa = 0.45$	0.035	0.60	0.031	0.12	0.047[e]
SUMMARY WEIGHTS	0.387		0.316		0.339		0.395

*Tables: [a]3.11; [b]3.12; [c]3.14; [d]3.13; and [e]3.16

It can be seen from the above table that Tishchenko's approach (using the weight-coefficient values given in Ref. 2) predicts the highest, and Boeing Vertol, the lowest, component weight values, while RTL results are in between. However, those differences are of a lesser concern, since variations in the weight ratios with respect to the corresponding items in the baseline helicopter and not their absolute values, are examined in this paper.

4. PARAMETRIC VARIATION

4.1 Ranges of Parametric Values

With respect to the design parameters (main-rotor disc loading, tip speed, and number of blades) whose variational influence on the five major component weights is investigated here, it is assumed that their values are constrained as follows:

(1) In addition to the baseline value of w_b = 8.77 psf, disc-loading parameter values ranging from 6.0 to 12.0 psf (which, for a constant gross weight, are synonymous with the main-rotor radius values) are considered.

(2) Also, in addition to the 670 fps tip speed of the base helicopter, two extra values of 620 and 720 fps are examined.

(3) The number of main-rotor blades of the baseline helicopter was assumed as 5, and the influence of varying that number to 4 and 6 is explored.

In order to simplify transcription of the formulas, ratios of the new parametric value to that of the baseline helicopter will be defined by a bar over the symbol. Consequently, the ratios symbolizing disc loading, tip speed, and number of blades will be: $w/w_b \equiv \overline{w}$, $V_t/V_{tb} \equiv \overline{V}_t$, and $n_{bl}/n_{bl_b} \equiv \overline{n}_{bl}$.

4.2 Modified Helicopter Characteristics

The influence of the above-expressed design-parameter ratios on the geometry of the main-rotor and helicopter as a whole can be expressed as follows.

Main-Rotor Radius:

$$R = R_b(\bar{w})^{-0.5} \tag{6}$$

Main-Rotor Blade Chord and Thickness:

$$c = c_b(\bar{w})^{0.5}(\bar{V}_t)^{-2}(n_{bl})^{-1} \tag{7}$$

$$t = t_b(c/c_b) \tag{8}$$

Main-Rotor rpm:

$$rpm = rpm_b(\bar{w})^{0.5}(\bar{V}_t) \tag{9}$$

Increase in Fuselage Length, Distance between Rotors and Tail-Rotor Drive-shaft Length:

$$\Delta L = R_b[(\bar{w})^{-0.5} - 1] \tag{10}$$

The approximate increase in fuselage wetted area (in feet) can be computed with the help of Eq. (10); assuming that the rear of the fuselage is visualized as a cone with a constant base having a radius of 4.5 feet:

$$\Delta S_f \approx 465[(\bar{w})^{-0.5} - 1] \tag{11}$$

Using Eqs. (6) through (11) and the basic data given in Table 1, all the necessary inputs needed to calculate the weights of the five major components can be obtained as long as the three design parameters vary within their assumed ranges.

5. EFFECTS OF PARAMETER VARIATIONS ON COMPONENT WEIGHT TRENDS

5.1 General

From Eqs. (1) through (5b), and with the additional information supplied by Eqs. (6) through (11), one can develop relatively simple expressions giving weight ratios for each of the modified components to the corresponding weights of the baseline helicopter as the parameters vary from their baseline levels. In this way, one would obtain an assessment of first-order effects of parametric variations on the weight trends of the components. This is supplemented by graphical presentation of weight ratios acquired from the actual weight estimates obtained from computer programs. It is obvious that in the latter case, second-order effects would also be reflected in the graphs (for instance, the influence of the last terms in Eqs. (1) and (1a) indicating weight increases when the blade becomes too slender, or having not enough thickness to meet droop conditions).

5.2 Main-Rotor Blades

The weight ratios of the main-rotor blades having varied parameters with respect to those of the baseline helicopter as developed from the equations of Tishchenko [T (Eq. (12)], Boeing Vertol [BV (Eq. 12a)], and RTL (Eq. 12b) are shown below, while the $(\overline{n_{bl}\,W_{bl}})$ weight ratios obtained from the computer program are presented in Fig. 2 as functions of single-parametric variations.

$$(\overline{n_{bl}}\,\overline{W_{bl}})_T = (\overline{w})^{0.35}(\overline{V_t})^{-3.4}(\overline{n_{bl}})^{-0.7} \tag{12}$$

$$(\overline{n_{bl}}\,\overline{W_{bl}})_{BV} = (\overline{w})^{-0.438}(\overline{V_t})^{-0.876}(\overline{n_{bl}})^{0} \tag{12a}$$

$$(\overline{n_{bl}}\,\overline{W_{bl}})_{RTL} = (\overline{w})^{-0.178}(\overline{V_t})^{-1.334}(\overline{n_{bl}})^{-0.313} \tag{12b}$$

From these formulas and Fig. 2, it can be seen that there are significant differences between the three compared methods regarding the weight effects of the deviation of design parameter values from their baseline levels.

With respect to the disc-loading influence, Tishchenko et al [Fig. 2(a)], indicates that reduction of disc-loading values below the baseline level of 8.77 psf should result in a decrease of the total blade weight. In contrast to the Soviet approach, Boeing Vertol and RTL methods predict a higher total blade weight than that of the baseline helicopter as the disc-loading values drop below 8.77 psf. It should be noted, especially in the Boeing Vertol case, that relative blade weights rise sharply as the disc loading approaches the 6 psf level. This is due to the secondary effects associated with blades having insufficient dimensional thickness (assuming that the airfoil relative thickness remains constant) to meet droop conditions without additional reinforcement.

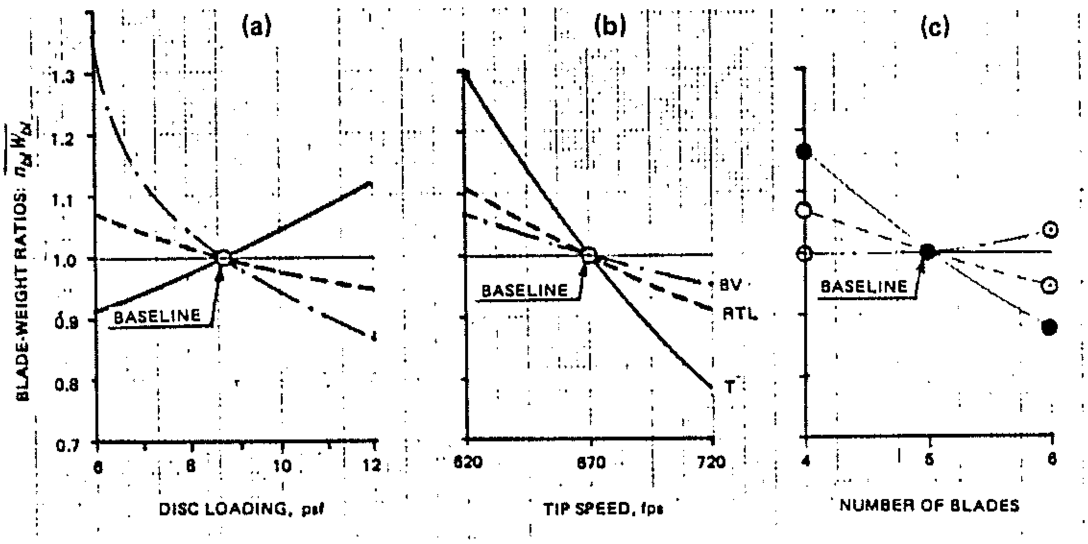

Figure 2. Baseline-related main-rotor blade weights vs. parametric values

As for deviation of the tip speed from its baseline value of 670 fps [Fig. 2(b)], all three methods are in agreement by indicating that $\overline{V_t}$ values higher than the baseline level would lead to a decrease; and those lower, to an increase in the total weight of the main-rotor blades. But considerable differences exist regarding the degree in the blade-weight variation as visualized by each of the three methods. It can be seen from Eqs. (12) through (12b) and from Fig. 2(b) that Tishchenko et al anticipate the largest, and Boeing Vertol the lowest weight benefits from increasing the tip speed over its baseline value.

The effect of the number of blades is assessed similarly by the Tishchenko and RTL methods [Eqs. (12), (12b) and Fig. 2(c)], as both indicate that a six-bladed rotor would have a lower; and four-bladed rotors, a higher total blade weight than the five-bladed baseline helicopter. However, the degree of these changes according to RTL would be lower than that visualized by Tishchenko. In the approach taken by Boeing Vertol, first-order effects [Eq. (12a)] would not show any change in blade weight as the number of blades varies. However, in actual blade-weight calculations, a slight increase in the relative blade weight should be noted as the number of blades is increased to 6 [Fig. 2(c)]. This, again, is due to the secondary effects of reduced dimensional blade thickness.

5.3 Main-Rotor Hub and Hinges

When the design parameters of the main-rotor hub and hinges are varied from their baseline level, the results of the weight ratios of the modified aircraft to those of the baseline aircraft can be analytically expressed as follows [Eqs. (13) through (13b)]:

$$(\overline{W}_h)_T = (\overline{w})^{1.147}(\overline{V}_t)^{-1.89}0.95[1 + 0.05(n_{bl} - 4)]\,(\overline{n}_{bl})^{-1.296} \quad (13)$$

$$(\overline{W}_h)_{BV} = (\overline{w})^{0.022}(\overline{V}_t)^{0.402}(\overline{n}_{bl})^{0.537} \quad (13a)$$

$$(\overline{W}_h)_{RTL} = (\overline{w})^{-0.88}(\overline{V}_t)^{-0.184}(\overline{n}_{bl})^{0.131} \quad (13b)$$

In Fig. 3, as in the preceding case, the corresponding weight ratios from the computer program are shown as functions of single parameters, and from this figure and Eqs. (13) through (13b), it can be seen that there is practically no agreement between the three weight-prediction methods examined here regarding the effect of the design-parameter variations on the relative weights of hubs and hinges.

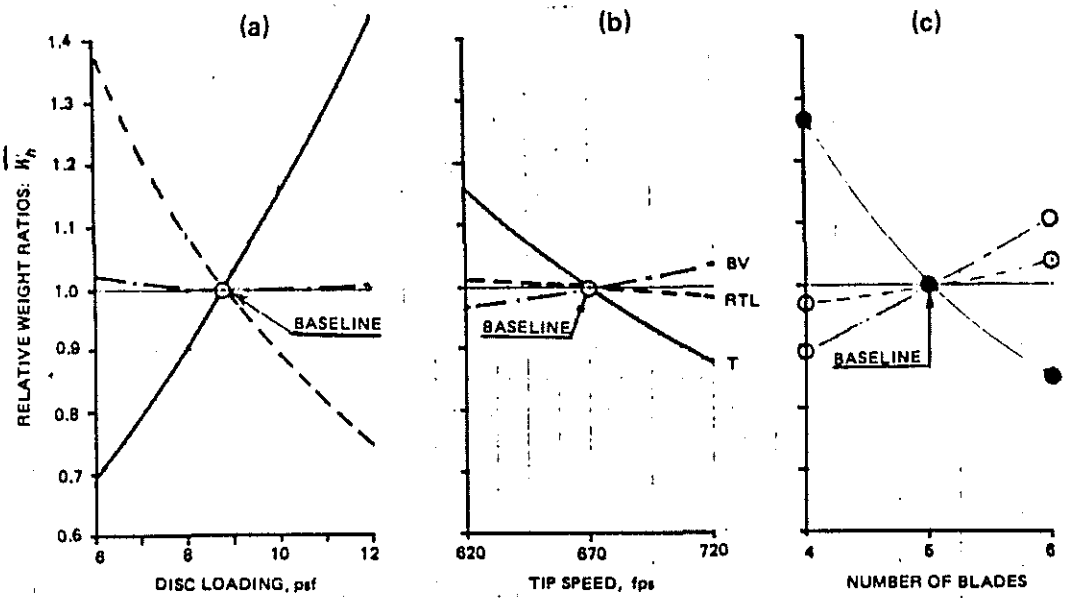

Figure 3. Ratios of hub and hinge weights to corresponding baseline weights, shown as functions of single parameters

For instance, with respect to the influence of disc loading [Fig. 3(a)], Tishchenko shows that reduction of parametric values below the baseline level would greatly reduce the relative hub and hinge weight, while the RTL approach implys just the opposite. In the Boeing Vertol approach, varying the disc loading has practically no effect on $\overline{W}_h$ values.

As far as tip speed is concerned [Fig. 3(b)], this time Tishchenko and Boeing Vertol represent opposite assessments of the merits of, say, increasing the tip speed above its baseline level — Tishchenko views such parameter changes as beneficial; Boeing Vertol as detrimental. In contrast to these approaches, RTL envisions little change in relative hub and hinge weights resulting from tip-speed variation.

As in the case of the two other parameters, confusion also exists regarding the significance of the number of blades [Fig. 3(c)], as Tishchenko indicates that increasing the number of blades to six would be beneficial, while Boeing Vertol claims the opposite. RTL shows little variation regarding the relative weight of the hub and hinges with respect to the number of blades.

5.4 Fuselage

Of the three design parameters, the weight of the fuselage is influenced by the disc loading only. Furthermore, one can see from Eqs. (3) through (3b) that the disc loading in the Tishchenko approach, through its inputs on the fuselage wetted area and distance between the rotors, influences the whole expression for fuselage weight. By contrast, in the Boeing Vertol and RTL methods, only some terms of the weight equations are affected by changes in disc-loading (again, through changes in the wetted area and some fuselage linear dimensions), while other terms of the equation remain unchanged. Consequently, in the fuselage-weight ratios developed from BV and RTL relationships, some fraction (ϵ) of that ratio would remain constant, while the $(1 - \epsilon)$ part would fluctuate with the disc-loading variation. Keeping this in mind, and taking into account Eqs. (10) and (11), the ratios of the fuselage weight with varied disc loadings to the weight of the baseline helicopter fuselage is expressed by the three compared methods as follows:

$$(\overline{W}_f)_T = \left\{1 + 0.3[(\overline{w})^{-0.5} - 1]\right\}^{0.88}\left\{1 + 0.81[(\overline{w})^{-0.5} - 1]\right\}^{0.16} \tag{14}$$

$$(\overline{W}_f)_{BV} = (1 - \epsilon)\left\{1 + 0.3[(\overline{w})^{-0.5} - 1]\right\}^{0.4} + \epsilon \tag{14a}$$

$$(\overline{W}_f)_{RTL} = (1 - \epsilon)\left\{1 + 0.3[(\overline{w})^{-0.5} - 1]\right\}^{0.153}\left\{1 + 0.515[(\overline{w})^{-0.5} - 1]\right\}^{0.556} + \epsilon \tag{14b}$$

where $\epsilon = 0.10$ is assumed in Eq. (14a) and 0.19 in Eq. (14b) (see Table 2).

The computer-derived weight ratios for the fuselage are shown in Fig. 4.

It is apparent from this figure as well as from Eqs. (14) through (14b) that, this time, all three methods are in agreement in predicting that a reduction of the disc loading below its baseline value would result in a heavier fuselage, while an increase in disc loading would result in a lighter fuselage than that of the original machine. However, there are some differences regarding the degree of the fuselage weight change sensitivity to the disc-loading variations. Looking at Fig. 4, one will note that the fuselage weight changes foreseen by the Tishchenko and RTL approaches are quite similar, and that both are relatively larger than those anticipated through the BV method.

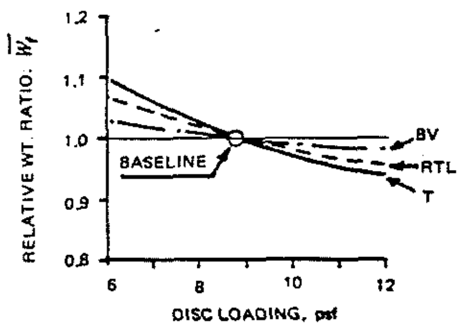

Figure 4. Ratios of relative fuselage weights to that of the baseline helicopter

5.5 Drive System

Looking at Eqs. (4) through (4b), one would note that only disc-loading and tip-speed values would influence the drive-system weights. Furthermore, it should also be noted that in all three equations there are terms that experience a change in magnitude under the influence of varying disc loading and tip speed (for instance, those terms representing main-gearbox weights) which would significantly alter the level of the drive-system weight as a whole. By contrast, there are other terms in these equations that would either not be affected by parametric variations or, even if affected, their contribution to the overall picture of the drive-system weight would be insignificant. Therefore, similar to the preceding case, the ϵ symbol is again incorporated into Eqs. (15) through (15b) — this time, representing the fraction of the total drive-system weight that either remains constant, or whose variation contributes little to the drive-system weight as disc loading and tip speed depart from their baseline levels.

$$(\overline{W}_{ds})_T = (1 - \epsilon)(\overline{w})^{-0.4}(\overline{V}_t)^{-0.8} + \epsilon \tag{15}$$

$$(\overline{W}_{ds})_{BV} = (1 - \epsilon)(\overline{w})^{-0.335}(\overline{V}_t)^{-0.69} + \epsilon \tag{15a}$$

$$(\overline{W}_{ds})_{RTL} = (1-\epsilon)(\overline{w})^{-0.345}(\overline{V}_t)^{-0.69} + \epsilon \tag{15b}$$

Values of ϵ appearing in the above equations are shown in Table 2, while the computer-determined relative drive-system weight values are shown in Fig. 5.

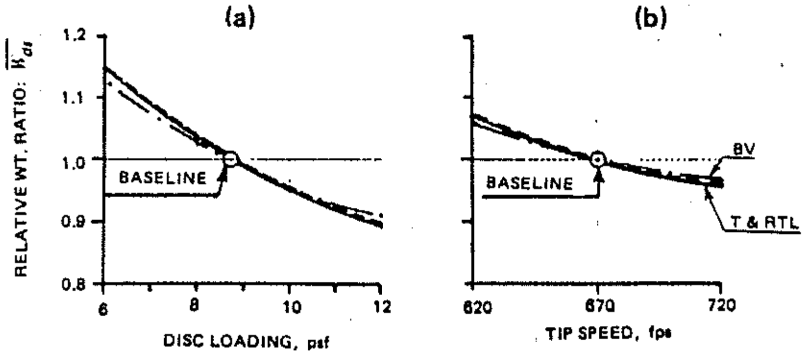

Figure 5. Baseline-related drive-system weights vs. disc loading and tip speed

It can be seen from Fig. 5 and Eqs. (15) through (15b) that there is close agreement among the three methods regarding the effects of deviations of disc loading and tip speed on the relative weight of the drive system. One can see that decreasing disc loading and tip speed below their baseline values would cause increases in weight, while increasing their values would result in lower weights. However, it should be emphasized at this point that both the equations and the figure were developed under the assumption of constant transmission power. Should the power be reduced with lower w and V_t values and increased with higher values, then the magnitudes, and even the signs, of the trends indicated in Fig. 5 could change.

5.6 Flight-Control Group

Examining Eqs. (5) through (5b), one would find that in the Tishchenko approach, the whole expression for the weight of the flight controls is affected by variations in the design parametric values. In particular, the first term in Eq. (5) (related to boosted controls) is a function of all three parameters, while the second term (reflecting the weight of so-called manual controls) is affected by disc-loading variation only.

Since both terms are of a similar order of magnitude, separate expressions are written for the relative weights of boosted and manual controls: $\overline{W}_{bc} = (\overline{w})^{0.5}(\overline{V}_t)^{-4}(\overline{n}_{bl})^{-1}$ and $\overline{W}_{mc} = (\overline{w})^{-0.5}$, respectively.

Assuming that manual controls in the baseline helicopter represent a fraction κ and the boosted controls, a fraction $(1-\kappa)$ of the total weight of the controls, an expression for the total controls-weight based on Tishchenko's approach is given in Eq. (16).

In the Boeing Vertol formula [Eq. (5a)], the first and third terms are invariant since, in this study, a constant gross weight is assumed. However, the second term would be affected by all three design parameters. Consequently, the ϵ concept is retained as in the two preceding cases, and an expression for the sought weight ratio can be written as in Eq. (16a).

In the RTL approach, the first term in Eq. (5b) remains invariant as the design parameters vary from their baseline levels. Thus, as in the Boeing Vertol case, the symbol ϵ is introduced into Eq. (16b).

$$(\overline{W}_{fc})_{T} = (1-\kappa)(\overline{w})^{0.5}(\overline{V}_t)^{-4}(\overline{n}_{bl})^{-1} + \kappa(\overline{w})^{-0.5} \tag{16}$$

$$(\overline{W}_{fc})_{BV} = (1-\epsilon)(\overline{w})^{0.03}(\overline{V}_t)^{-2.44}(\overline{n}_{bl})^{-1.1} + \epsilon \tag{16a}$$

$$(\overline{W}_{fc})_{RTL} = (1-\epsilon)(\overline{w})^{0.22}(\overline{V}_t)^{-0.9}(\overline{n}_{bl})^{-0.45} + \epsilon \tag{16b}$$

Flight-control weight ratios, determined from the computer program, are shown in Fig. 6.

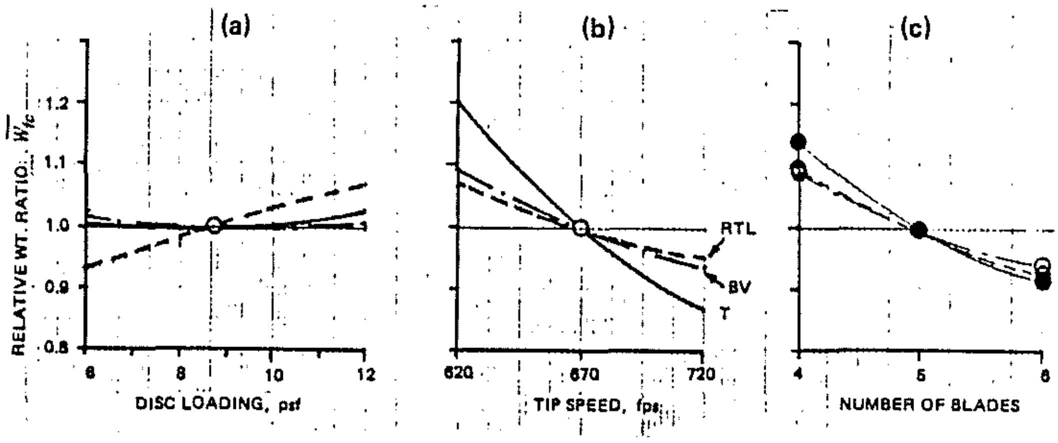

Figure 6. Baseline-related flight-control weight ratios vs. three design parameters

Looking at Eqs. (16) through (16b) and, in particular, at Fig. 6, one would find that there is a good agreement between the three methods regarding the role of the number of blades; i.e., a helicopter with a six-bladed rotor would have lighter, and four-bladed rotors, heavier flight controls than the baseline five-bladed machine [Fig. 6(a)].

There is also a general agreement [see Fig. 6(b)], that an increase in tip speed above the baseline level would contribute to a reduction in of the relative weight of the flight controls, while a decrease in V_t would increase the weight. However, there are some differences between the Tishchenko approach and its Western counterparts: Tishchenko anticipates the influence of the design tip-speed variation to be about twice as high as the two Western methods.

Both Tishchenko and Boeing Vertol methods indicate that variation in disc loading has practically no effect on the flight-control weight ratios. In the case of Tishchenko, this results from the fact that relative weights of both boosted and manual flight controls [first and second terms in Eq. (16), respectively] are oppositely affected by disc-loading variations. Furthermore, since there is very little difference in the values of the $(1 - \kappa)$ and κ coefficients (0.55 in the first case, and 0.45 in the second), the effects of disc loading variations on boosted controls tend to practically cancel out those same effects with respect to manual controls.

In the Boeing Vertol case, the disc-loading ratio is to a very low power of 0.03. Thus, the disc loading is significant in the RTL formula only [Eq. (16b) and Fig. 6(a)].

6. EFFECT OF PARAMETRIC VARIATIONS ON SUMMARY WEIGHT

6.1 Analytical Presentation

Eqs. (12) through (16b) provide expressions for the weight ratios of major components as anticipated by the three compared methods. Using these equations, it becomes easy to write an expression for summary weight ratios of the modified components to their baseline counterpart. Denoting this summary weight ratio by $\overline{W_\Sigma}$, it may be expressed as follows:

$$\overline{W_\Sigma} = [(\widetilde{n_{bl}W_{bl}})(\overline{n_{bl}W_{bl}}) + (\widetilde{W_h})(\overline{W_h}) + (\widetilde{W_f})(\overline{W_f}) + (\widetilde{W_{ds}})(\overline{W_{ds}}) + (\widetilde{W_{fc}})(\overline{W_{fc}})]/(\widetilde{W_\Sigma}) \qquad (17)$$

where the symbols denoted with curved bars as superscripts represent ratios of the major component weights of the baseline helicopter to the design gross weight of that machine.

Eq. (17) is, of course, a function of the design parameters, thus the structure of this function would be different for each of the three compared weight-prediction methods.

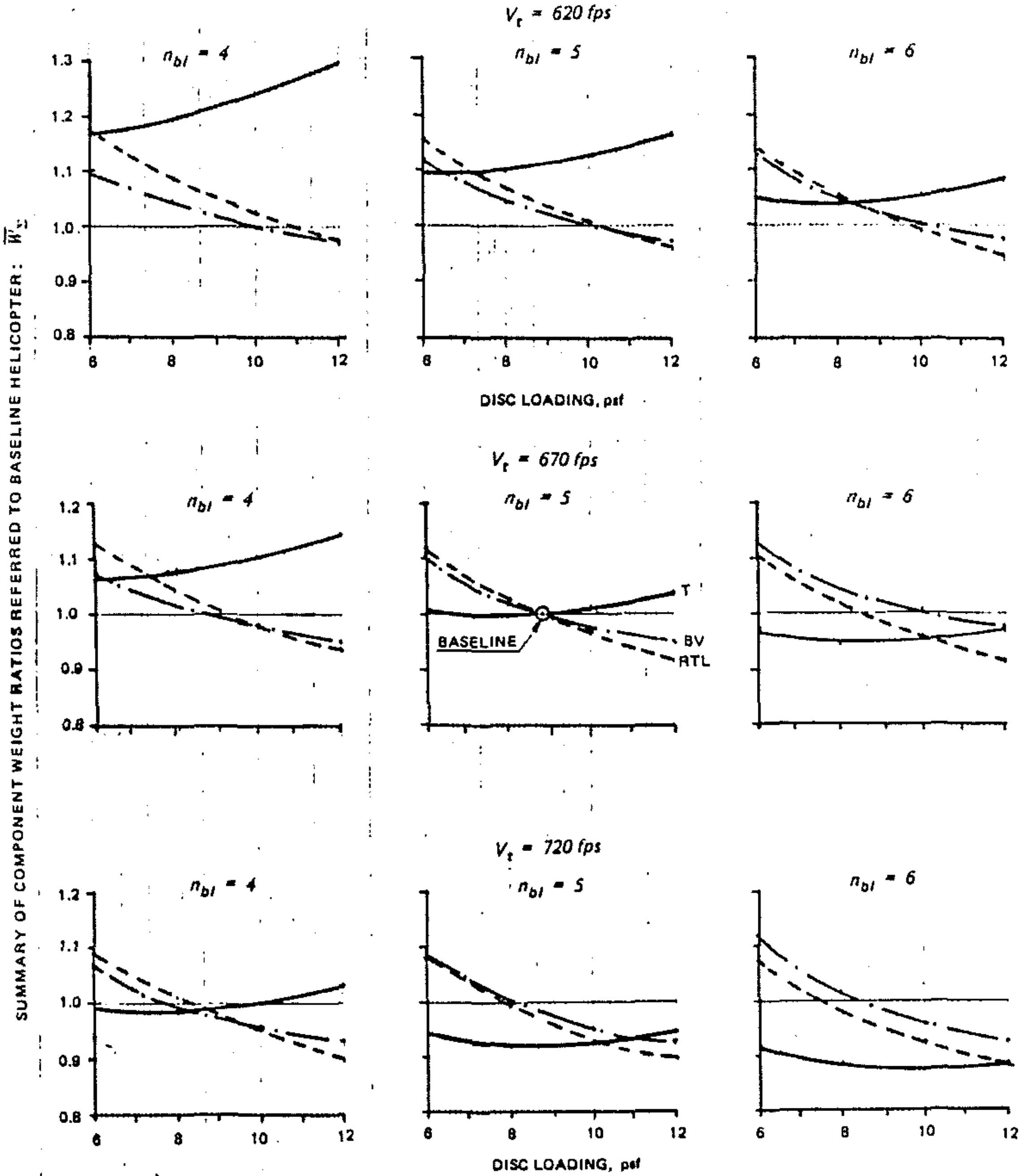

Figure 7. Relative summary weights as functions of disc loading, tip speed, and number of blades

Finding a set of design parameter values (or their ratios to those of the baseline helicopter) which would make Eq. (17) a minimum would constitute the weight-optimization process.

Since, in this paper, the number of design parameters was limited to three, the use of a graphical approach (which will be discussed in the following section) may be quite appropriate for finding the optimizing set of design parameters. Should, however, the number of the considered design parameters become more than three; for instance, by including C_T/σ as a variable, then more sophisticated methods of finding a minimum of a multivariable function would have to be used.

6.2 Graphical Presentation

As mentioned in the preceding section, the use of graphical techniques may be quite suitable when only three design parameters are considered as independent (control) variables in the weight-optimization process. This procedure is shown in Fig. 7 where it should be noted that ratios directly obtained from the computer program; and not those based on Eq. (17), are plotted. However, since differences in the weight ratios as given by Eqs. (12) through (16b) and those obtained from the computer program were minimal, Fig. 7 may be considered as fully representative of Eq. (17).

Looking at this figure, one will note that for each of the three considered tip speeds, the summary weight ratios are plotted vs. disc loading when the number of blades total 4, 5, or 6. It is obvious that combinations of the design-parameter values leading to summary weight ratios greater than one represents an increase, and those lower than one, a decrease in the structural weight of the modified helicopters when compared to that of the baseline machine. A set of design parameters associated with the lowest $\overline{W}_{\Sigma}$ value would constitute the optimal combination of those parameters from the structural weight point of view.

7. DISCUSSION

An examination of Fig. 7 would indicate that there are considerable differences with respect to the trends in the summary weight ratios as anticipated by Western methods as opposed to the Soviet method. The Western approaches suggest that an increase in disc loading is definitely beneficial for the structural weight reduction at any of the combinations of tip speed and number of blades considered in this paper. As a matter of fact, Boeing Vertol and RTL both imply that it is desirable to go with disc loading all the way up to its maximum constrained value of 12 psf.

By contrast, Tishchenko seems to indicate that for a combination of a low tip speed (620 fps) and 4 or 5 blades, and a tip speed of 670 fps and 5 blades, it should prove beneficial for structural weight to have the lowest permissible disc loading (at least, until weight penalties associated with the blade-droop condition reverses the trend). It should be noted, however, that regardless of the benefits of a low disc loading, the basic combination of a low tip speed (620 fps) and a small number of blades (4) is very detrimental, weight-wise.

One should also note that in addition to the above-discussed case of low tip speeds and small numbers of blades, differences between Western and Soviet predicted trends of relative summary weights vs. disc loading still persist for other combinations of tip speeds and numbers of blades. This obviously stems from the radically different assessments by the Soviet and Western methods of the role of the disc-loading level in the cases of weight trends for blades and hubs plus hinges.

In view of all the differences in the relative summary weight trends, it is somewhat surprising that all three methods converge by showing that an optimal in the case of Western approaches, and almost optimal in Tishchenko's judgement combination of design parameters, would consist of a disc loading of 12 psf, tip speed of 720 fps, and six blades. It is true that in Tishchenko case, actual optimum occurs at a disc loading of approximately 9.5 psf, but the difference in the relative summary weight corresponding to the latter value and that of 12 psf is very small. It is also interesting to note that both Tishchenko and RTL methods suggest that by going to the optimal permissible combination of design parameters, the summary weight of the five major components can be made more than 10 percent lower than that of the baseline helicopter. The Boeing Vertol approach is more conservative in that respect by indicating that those gains would amount to about 7 percent.

With respect to the reliability of the structural weight minimization process discussed here, it is obvious that the final results are only as good as the relationships showing the influence of design parametric variation on the relative weights of the major components. In that respect, one would have a greater confidence in the expression for the $\overline{W}$ values for such major components as fuselage, drive system, and flight controls where the three methods considered here are approximately in agreement, than in the case of blades and hub and hinge weights, where considerable differences exist. At this point, it is difficult for the authors to pronounce judgement as to which of the methods in this latter case are right and which are wrong. It may be pointed out that only in those cases (fuselage, drive system, and flight controls) where a general agreement among the three methods does exist, that basic weight-prediction equations [Eqs. (3)

through (5b)], all to some degree reflect the physical significance of the relationship between the parameter and weight changes. For instance, in the case of the drive system, variations in disc loading and tip speed clearly translate into changes in the torque carried by the transmission system which, in turn, directly affects dimensions of various parts of the system and thus, its weight.

In the case of blades and hubs and hinges, there is not such a clear-cut, physically obvious, relationship between the design parameter variations and component weight changes. For this reason, it appears that it would be desirable to develop relationships—perhaps separately for several types of blades and hubs based on proper physical models – which would show how the relative weight of blades and hubs plus hinges would change as basic design parameters begin to deviate from those of the baseline component.

8. CONCLUDING REMARKS

Structural weight minimization techniques based on the examination of the major component weight ratios with respect to their counterparts in a baseline aircraft appears to be suitable for preliminary design practice. However, the results shown by the methods developed in this paper must be used with caution. It is very important to keep in mind the assumptions and constraints which were applied in this particular exercise.

It should also be recalled at this point that the design parameter selection shown in this paper emphasize the weight minimization aspects only. An actual in-depth preliminary design optimization would involve many more areas of consideration such as cost, (see, for instance, Ref. 9), noise reduction, crashworthiness, and reliability and maintainability. Even in the weight area, many more possibilities of weight minimization could have been addressed; i.e., technology. But time and resources were limited. If time and resources were made available, a very interesting effort could be undertaken to expand the weight optimization study by selecting more than just three design parameters and possibly gathering together a few more weight-prediction methods (perhaps from European countires) and then analyzing the effects that these weight-prediction methods would have on helicopters representing several gross-weight classes (for example, as in Ref. 2 where helicopters weighing up to 12,000 pounds, 12,000 to 30,000 pounds, and 30,000 to 100,000 pounds were considered).

The weight equations presented in this report were derived on statistical bases, using data from existing air vehicles; thus the use of weight equations beyond the scope of the data base must be done by exercising a little engineering judgement. For this reason, a study of the physical aspects of the interaction between various inputs reflecting design parameter variations and changes in the relative weights of major helicopter components would be very desirable. Expressions for the relative weights derived on this basis would form a truly reliable foundation for the weight-minimization process along the lines described in this paper.

Acknowledgements:

The authors wish to thank Mrs. Wanda L. Metz for her never-ending dedication to the technical accuracy, consolidation, and editing of this paper. The many hours of very hard and concentrated work are very much appreciated. We also wish to express our indebtedness to the management of Boeing Vertol Company and, in particular, to Mr. Euan Hooper for reproducing preprints of this paper and shipping them to the Forum.

References

1. Stepniewski, W.Z. and R.A. Shinn. *Soviet vs. U.S. Helicopter Weight Prediction Methods.* Paper A-83-39-65-1000 presented at the 39th AHS Forum, May 9-11, 1983.

2. Stepniewski, W.Z. and R.A. Shinn. *A Comparative Study of Soviet vs. Western Helicopters:* Part II, *Evaluation of Weight, Maintainability and Design Aspects of Major Components.* NASA Report CR 3880, March 1983.

3. Tishchenko, M.N., A.V. Nekrasov, and A.S. Radin. *Viertolety vybor parametrov pri proektirovaniy (Helicopters, Selection of Design Parameters).* Mashinostroyeniye Press, Moscow, 1976.

4. Davis, Jon and J.S. Wisniewski. *User's Manual for HESCOMP — The Helicopter Sizing and Performance Computer Program.* Developed by Boeing Vertol Co. for NASA, D210-10699-2, Sept. 1973. Revised Nov. 1974.

5. Shinn, R.A. *Group Weight Estimation for the Advanced Scout Helicopter Design Study.* SAWE Paper No. 1445 presented at the 40th Annual Conference on Mass Properties Engineering. Dayton, Oh. May 1981.

6. Wartenberg, Steve. *AHS/HAI Commercial Users Design Conference.* Vertiflite, Vol. 29, No. 2, Jan/Febr. 1982.

7. Mills, Stanley. *The Next Generation 24-30 Passenger Commercial Helicopter.* Presented at the AHS Mini Forum at Boeing Vertol, Dec. 14, 1982.

8. Fay, Charles B. *Speed and Power Margin Overview.* Presented at AHS/HAI Commercial Users Design Conference, Nov. 4-5, 1982.

9. Stepniewski, W.Z. and L.H. Sloan. *Some Thoughts on Design Optimization of Transport Helicopters.* Vertica, Vol. 6, No. 1, Jan. 1982.