A number of cases were run and a comparison of the ML method with the Extended Kalman Filter for combined State and Parameter estimation was also made. The convergence of the ML algorithm, the parameter estimates and their standard deviations were much more satisfactory than those of the Extended Kalman Filter. Some of the results are shown in Figs. 9a and 9b and Table 3. It is seen that an order of magnitude improvement in standard deviations can be obtained by using the multistep input over the single-step input. The estimates of the total forces and moments (Fig. 9a and 9b) are also satisfactory, though the estimates of all the polynomial coefficients are not always as good. Further details on the results are contained in Refs. 7 and 8.

6. Conclusions

The generalized Maximum Likelihood Method which includes the Output Error Method and the Equation Error Method as special cases has been applied to flight test data from HL-10 and M2/F3 lifting bodies. Accurate fits to the time histories are obtained even in the presence of lateral gusts when the output error method leads to a very poor match with the time histories. The maximum likelihood method is extended to nonlinear dynamics with process noise and is applied to simulated data on X-22 longitudinal equations of motion. A marked improvement in identification from using a multistep input as opposed to a single step is demonstrated.

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The Cost of Noise Reduction in Intercity Commercial Helicopters

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The relationship between noise reduction and direct operating cost was studied for commerical helicopters having a design range of 400 miles. This was accomplished by generating a large number of helicopter preliminary designs with the aid of a computer program. Designs were selected to meet each of four noise level goals with minimum direct operating cost, establishing a curve of noise level vs direct operating cost. This was repeated for several payloads and technology time frames. It was concluded that good economic performance can be expected of relatively quiet future helicopters which have low tip speeds and high solidity rotors. With a 25% increase in direct operating costs the takeoff perceived noise level at 500 ft for a 1975, 50 passenger helicopter can be kept below 80 dB PNL. The expected improvements in helicopter technology over the next fifteen years can offset the economic penalties due to noise reduction.

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Index categories: VTOL Aircraft Design; VTOL Missions and Transportation Systems.

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Nomenclature

$\mu = (V)/(V_{tip})$ = rotor advance ratio
ρ_{cr} = air density in cruise regime, slugs/ft^3
ρ_h = air density in hover and low speed regime, slugs/ft^3
$\sigma = (A_B)/(R^2)$ = rotor solidity
ϕ = angle between the rotor axis, and a line joining the rotor hub, and a ground observer
A_B = total rotor blade area, ft^2
C = rotor blade mean chord, ft
$\bar{C}_L$ = rotor blade mean lift coefficient
C_T = rotor thrust coefficient = $(T)/(\rho\pi R^2 V_{tip}^2)$

$(C_T/\sigma)_h$	= rotor thrust coefficient to solidity ratio in hover and low speed regime
$(C_T/\sigma)_{cr}$	= rotor thrust coefficient to solidity ratio in cruise regime
D	= rotor diameter, ft
DF	= noise directivity factor
DL	= disc loading, lb/ft^2
DOC	= direct operating cost, $/seat trip
GW	= gross weight, lb
$(L/D)_{cr}$	= lift to drag ratio in cruise
L_p	= over-all sound pressure level, dB
L_{PN}	= perceived noise level, dB
$(L_{PN})_{cr}$	= perceived noise level in cruise, dB
$(L_{PN})_{to}$	= perceived noise level at liftoff, dB
M_{at}	= advancing tip Mach number
NRP	= normal rating of installed power plant, hp
R	= rotor radius, ft
T	= total thrust, lb
V	= vehicle forward speed, fps
$V_{0.7}$	= rotor blade speed at 70% radius, fps
V_{cr}	= cruise speed, mph
Vt_{cr}	= rotor tip speed in cruise regime, fps
Vt_h	= rotor tip speed in hover and low speed regime, fps
V_{tip}	= rotor blade tip speed, fps

Introduction

THE helicopter has the potential to become an important means of transportation in densely populated regions. Land is scarce and surface transportation is slow in these regions. Here the higher operating costs of the helicopter can be offset by its small land requirements and the resulting ability to locate numerous terminals close to centers of demand. In the next decade helicopter transportation in urban areas may be expected to expand considerably if vehicles designed for civil transport become available. In this report the emphasis is on helicopters for intercity transportation, covering stage lengths of 50 to 400 miles. However, the results apply in a general way to helicopters operating on shorter stage lengths.

In recent years a strong adverse public reaction to aircraft noise has developed. Noise reduction is now an important, if not dominant, objective in air transportation planning. The helicopter is inherently relatively quiet due to its low disc loading and low flow velocities in and around the propulsion device. However, it appears that helicopters will have to be still quieter in the future to retain community acceptance while services expand. This is particularly true in the case of intercity service which would involve large vehicles and high frequency of operations at some terminals. Because of the small size of the vertiport, the aircraft operations are closer to the surrounding nonuser population. Furthermore, it may be desirable for demand reasons to locate terminals in areas having a relatively low background noise level, such as residential areas. The question arises as to what degree of noise reduction can reasonably be expected in the future. In other words, it becomes necessary to know what is the relationship between noise reduction and cost increases.

There are two methods of reducing the noise exposure due to aircraft operations. One is to change the flight profile. This method of noise reduction is explored for VTOL aircraft in Refs. 1 and 2. The second method is to change the design of the aircraft to reduce the noise generated at a given distance, thrust level, and speed. The second method is considered here.

The purpose of this work is to identify those design changes which can reduce noise with the minimum cost penalty and to develop the relationship between the amount of noise reduction and the resulting cost penalty. Miller[3] performed an initial study of these questions. By developing a series of helicopter preliminary designs, he explored the relationship between design parameters, direct operating cost, and noise generated. A computer program was used to aid in the design iterations. Curves of hover noise vs hover tip Mach number and direct operating cost (DOC) vs hover noise were developed for a series of 80 passenger helicopters. These curves were generated by varying either the hover tip Mach number, or the thrust coefficient to solidity ratio, while holding other parameters constant.

In this work a different approach is taken using a more sophisticated helicopter design computer program. Takeoff and cruise noise objectives were set along with size, technology time frame (year of first flight), and operational constraints. Then all other parameters were varied to produce a vehicle with minimum direct operating cost which met the noise objectives. This was then repeated for three other levels of noise objectives to find the relationship between noise level and direct operating cost. This basic variation was then extended to different sizes and time frames. Additional results and discussion may be found in Ref. 4.

Design Logic

The helicopter computer design program is fully described in Ref. 5. This program considers only conventional pure helicopters. A flow chart is shown in Fig. 1.

The program begins by reading input data such as cabin size, range, speed, etc. and generating constants, including atmospheric data, for later use. Calculations regarding hover performance are done for a hot day; all other calculations assume a standard day.

Then the program goes into a design procedure which is an iteration on gross weight. Initially a gross weight is estimated based on the design payload; on succeeding iterations the previous gross weight is used. The rotor is then designed considering both cruise and hover. It is assumed that there are two rotor angular velocities: the rotor turns at hover rpm when the advance ratio is less than 0.325 and cruise rpm otherwise. This is accomplished by changing the speed of the engine free turbine and the penalties in power available are estimated based on data for the T64-GE-12 engine. Next the fuselage is sized and parasite drag is calculated. Then the power plant and drive system is sized to the maximum of cruise and hover requirements. This completes the selection of design parameters.

The vehicle is then flown through the design mission to find the fuel consumed. Nine phases in the mission profile are considered: vertical climb, acceleration to climb advance ratio, unaccelerated climb to cruise altitude, acceleration to cruise, undecelerated descent, deceleration to hover, vertical descent, and hover. During the acceleration phase, the vehicle tries to accelerate horizontally at a given maximum acceleration; and, if it has more than enough power to do this, it uses the excess power to climb. The time, distance, and fuel consumed in each phase is calculated. An input table of rotor lift-to-drag ratio as a function of advance ratio and thrust coefficient to solidity ratio is used to estimate performance above advance ratio 0.325.

Then the component weights are calculated, resulting in a new gross weight. If the difference between new and old gross weights is greater than a specified amount, the design procedure goes through another cycle. When the iteration is complete the parameters describing the final design are printed.

Vehicle Operating Cost

The vehicle then is flown through various stage lengths that are less than the design range, with appropriate cruise altitudes and speeds. The time, distance, and fuel consumed for each phase of each stage is calculated,

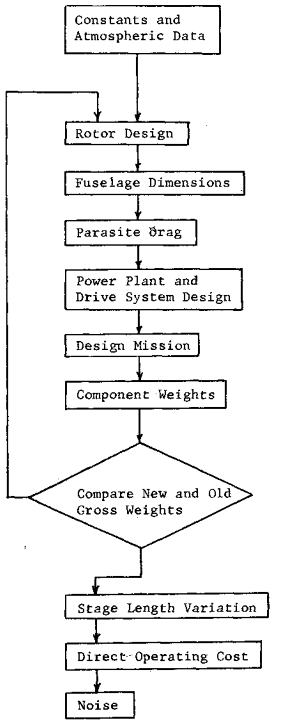

Fig. 1 Flow chart for helicopter design computer program.

printed, and stored for use in the calculation of direct operating cost (DOC).

Then the program calculates DOC's for each stage length, breaks them down by categories, and prints this out. The DOC is calculated according to the Lockheed/New York Airways VTOL formula.[6]

Vehicle Noise Generation

As the last step, the program calculates the noise generated by the vehicle. There are three principal noise sources in a helicopter: the rotors, the engine, and the transmission. Modern commercial helicopters are powered by turboshaft engines. The methods used to quiet these engines and the transmission are quite straightforward and have a relatively small effect on DOC. This effect is accounted for by assuming a weight penalty in the engine. The input horsepower/weight ratio is decreased approximately 20% for each 10 dB of rotor noise reduction below 90 dB perceived noise level at 500 ft. Above 90 dB no penalty is assumed. The weight penalty for quieting the tail rotor on single rotor ships is assumed to be insignificant. Thus noise sources other than the main rotor(s) are assumed to be quieted below the level of the main rotor(s).

Over-all sound pressure level for the rotor (s) at 300 ft distance is calculated using the following well established empirical formula taken from Ref. 7 for vortex noise

$$L_p = 10 \log_{10}[3.81 \times 10^{-10}(V_{0.7})^6 A_B \bar{C}_L{}^2]$$

Rotational noise was calculated for a number of sample cases using the method of Ollerhead and Lowson.[8] The results indicated that level of rotational noise was comparable to the level of vortex noise only for helicopters with high tip speeds traveling at cruise speed. Therefore the calculation of rotational noise was not included in the program. Recent research[9] has indicated that a large part of what used to be thought of as vortex (broadband) noise may in fact be largely composed of rotational noise. This does not affect the accuracy of empirical predictions of overall sound pressure level, however.

Simple inverse square law attenuation is used for observer distance other than 300 ft from the vehicle. The observer is always assumed to be directly underneath the flight path and hence directivity in azimuth is not considered. The method given in Ref. 8 for vortex noise is used for directivity in elevation. A factor DF is added to the overall sound pressure level

$$DF = 10 \log_{10}\left[\frac{\cos^2\phi + 0.1}{\cos^2 70° + 0.1}\right]$$

This factor varies from +7 along the shaft axis to −0.35 in the rotor plane. The overall sound pressure level is converted to perceived noise level using an assumed frequency distribution from Ref. 10, resulting in the following simple relation:

$$L_{PN} = L_P + 9.2 + 0.0125 V_{tip}/c$$

As the vehicle accelerates from rest to its vertical rate of climb, thrust is greater than weight and hence more noise is generated. The noise resulting from maximum thrust is calculated and assumed to represent the noise in the first few seconds of the takeoff profile. This is called noise at lift-off. The noise on the ground is calculated for an observer at 15 points during the takeoff profile and output along with the time, altitude and horizontal distance corresponding to each point. This can be repeated for observers at different distances from the takeoff point. The observers are always in the plane of the takeoff profile. Noise on the ground due to the vehicle passing directly overhead at cruise altitude is also calculated, using the advancing blade tip speed in the same formula. This value is assumed to represent the peak flyover noise which would occur when the vehicle is approaching rather than flying overhead.

Variation of Design Parameters for Noise Reduction

The formula for overall sound pressure level given above can be rewritten as follows:

$$L_P = 10 \log_{10}\left[1.71 \times 10^{-9}\left(\frac{C_T}{\sigma}\right)^2 A_B V_{tip}{}^6\right]$$

Two regimes are considered, characterised by different rotor angular velocities, as discussed above under design logic. These are referred to as the hover and cruise regimes. The thrust of the main rotor(s) is approximately equal to the gross weight both in the hover regime and in the cruise regime

$$T = \rho_h V_{th}{}^2 A_B (C_T/\sigma)_h = \rho_{cr} V_{tcr}{}^2 A_B (C_T/\sigma)_{cr}$$

$(C_T/\sigma)_h$ is proportional to blade lift coefficient and can be only raised slightly without bringing on blade stall. Thus, for the purposes of this discussion, T, ρ_h, ρ_{cr}, and $(C_T/\sigma)_h$ may be considered constant. Therefore, turning to the hover regime, A_B is inversely proportional to $V_{th}{}^2$. Then, substituting for A_B in the first equation above, L_p is proportional to the logarithm of the fourth power of V_{th} only. Thus, V_{th} is the controlling design parameter, and as it is reduced to reduce noise, A_B is increased. Turning now to the cruise regime, a similar argument could be made, but A_B is fixed by the hover regime and $(C_T/\sigma)_{cr}$ is varied to keep thrust constant. In this study we wished to reduce noise in both regimes, but more so in the hover regime. Thus: V_{th} and V_{tcr} were both reduced but V_{th} more so. Hence A_B was increased and $(C_T/\sigma)_{cr}$ was reduced. Each of these changes results in some penalty in performance. The net effect of all the changes is that rotor and drive system weights are increased and cruise speed is decreased.

The noise prediction formula used here was developed from a correlation of design parameters with measurements of noise from helicopters and rotors. These helicopters and rotors had solidities and disc loadings typical of

Table 1 Input constants

Design range	400 miles
Height of vertical climb	500 ft
Cruise altitude	5000 ft
Maximum acceleration	0.25 g
Climb advance ratio	0.30
Standard temp.	59°F
Hot day temp.	95°F
Reserve	20 min at cruise power
Rate of vertical descent	600 ft/min
Allowable deceleration	0.20 g
Utilization	2,300 hr/year
Depreciation period	12 years
Airframe cost	70 $/lb
Engine cost	50 $/hp
Insurance rate	2 %/year
Maintenance labor rate	5 $/hr

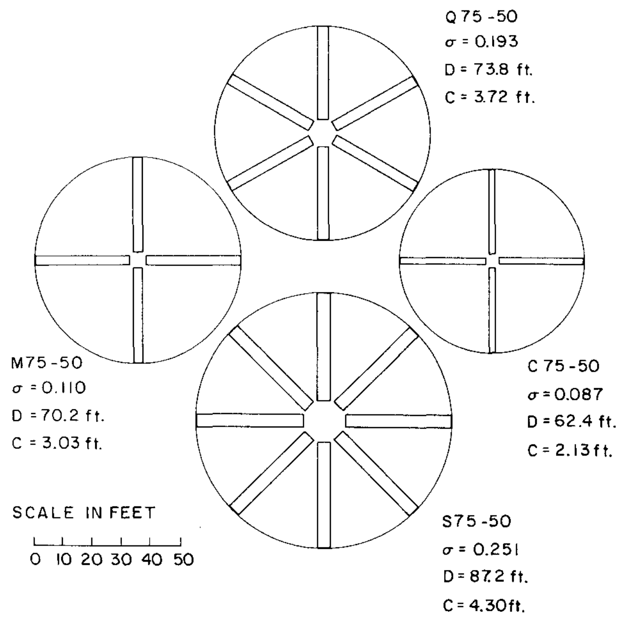

Fig. 2 Rotors for tandem basic helicopters.

designs which are unconstrained by noise considerations. As the solidity is increased and disc loading reduced to reduce noise, this emprical noise prediction formula becomes less valid. Further experimental data on the noise generation of low disc loading high solidity rotors is required to develop a more generalized formula. Until this is available, prediction of large noise reductions based on this formula must be regarded as preliminary. The same argument can be applied to the method of predicting high speed rotor performance. Experimental performance data is also needed for high solidity, low disc loading rotors.

Table 2 Rotor equivalent lift/drag ratio as a function of advance ratio, μ, and thrust coefficient to solidity ratio, c_T/σ

				μ			
c_T/σ	0.30	0.35	0.40	0.45	0.50	0.55	0.60
0.030	4.4	4.9	5.1	5.0	4.7	4.3	4.2
0.035	5.2	5.8	6.0	5.8	5.6	5.1	4.9
0.040	5.9	6.6	6.8	6.6	6.4	5.8	5.6
0.045	6.6	7.3	7.5	7.4	7.1	6.5	6.2
0.050	7.3	8.1	8.3	8.1	7.8	7.1	6.9
0.055	7.8	8.6	8.9	8.7	8.3	7.6	7.3
0.060	8.3	9.1	9.4	9.2	8.8	8.1	
0.065	8.5	9.4	9.7	9.5	9.1	8.3	
0.070	8.6	9.5	9.8	9.6	9.2		
0.075	8.4	9.3	9.6	9.4	9.0		

Note: This table was derived using the performance of existing helicopters and preliminary rotor performance prediction studies in the Flight Transportation Laboratory.

Table 3 Parameters describing four basic helicopters and E70-50

Parameters	E70-50	C75-50	M75-50	Q75-50	S75-50
$L_{PN}{}^{\circ}$ dB	95.0	93.6	85.2	79.2	74.9
L_{PNcr} dB	84.1	82.5	77.6	73.2	69.4
DOC @ 100 mi, $/seat trip	4.36	3.36	3.65	4.25	5.23
GW, lb	46,186	36,774	38,637	42,739	47,855
NRP, hp	7133	6280	5964	6593	6570
DL, lb/ft²	8.2	6.0	5.0	5.0	4.0
σ	0.089	0.087	0.110	0.193	0.251
V_{cr}, mph	189	237	219	196	168
$(L/D)_{cr}$	4.31	4.89	5.00	5.07	5.42
μ	0.40	0.50	0.55	0.60	0.60
M_{at}	0.883	0.95	0.825	0.70	0.575
$(C_T/\sigma)_{cr}$	0.093	0.070	0.065	0.055	0.050
V_{tcr}, fps	692	694	584	480	411
$(C_T/\sigma)_h$	0.081	0.063	0.100	0.100	0.100
V_{th}, fps	692	680	437	330	270

Variations in detail rotor blade geometry are not considered here. New tip planforms and twist distributions can reduce noise somewhat but not dramatically. Research has not gone far enough to develop analytical relationships which could be used in this study. These changes do not generally result in a significant weight or performance penalty, and hence do not affect DOC. Therefore these changes will move the whole curve of noise vs. DOC downward slightly without changing its shape.

Design Constants

All of the helicopters in this paper, except E70-50, are designed to be able to hover on a hot day with one engine out.

A number of inputs to the helicopter design computer program were kept constant throughout the work reported here. The values of these are presented in Table 1. Table 2 shows the rotor equivalent lift to drag ratio as a function of advance ratio and thrust coefficient to solidity ratio.

Results

Nomenclature for Helicopter Designs

The helicopter designs described here are designated by codes consisting of a letter and two numbers. The letter indicates the noisiness class according to the following mnemonics:

C–Cheap–unconstrained
M–Medium–moderately quiet
Q–Quiet–very quiet
S–Silent–extremely quiet

The first number indicates the technology time frame. Here the time frame is the year in which a production prototype could be flying, using the latest technology both in design and manufacturing. The second number indicates the size as measured by passenger seats. For example, Q75-50 is a very quiet helicopter, designed using 1975 technology and carrying 50 passengers. An exception to this is E70-50, which represents an approximation of a helicopter existing in 1970, the Vertol 347.

Basic Variation

The basic variation consists of four tandem helicopters, designed to meet four different noise level objectives. The payload (50 seats), design time frame (1975), and operational constraints were kept constant. All other parameters were varied to produce vehicles which met the noise

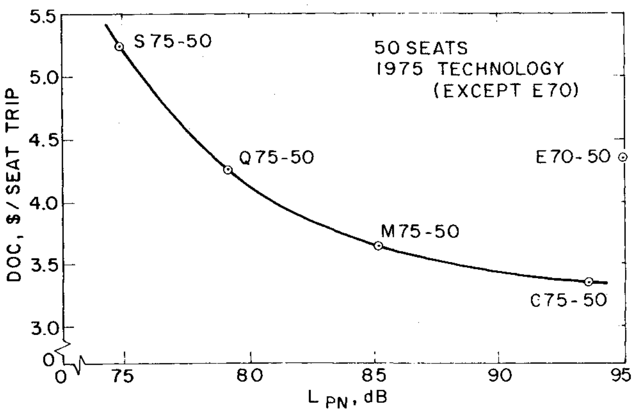

Fig. 3 DOC @ 100 mile vs liftoff noise @ 500 ft for basic helicopters.

objectives with minimum direct operating cost, as shown in Table 3. The rotors for the four basic helicopters are shown in Fig. 2. The fifth vehicle shown in Table 3, E70-50, was included to add perspective by showing what is available now. It has the same payload, range and operating constraints as the other machines, but lacks engine out hover capability. The *C* and *S* vehicles were chosen to represent the extremes of the noise level spectrum for this kind of aircraft. It is unlikely that any future civilian transport helicopter would be designed without regard for noise reduction, as the *C* vehicle is. The *S* vehicle, on the other hand, carries the noise reduction techniques described to the fringe of practicality.

Most of the parameters in Table 3 show a monotonic variation with noise level. It is interesting to note that overall lift to drag ratio increases with decreasing noise level because cruise speed is decreasing. DOC is plotted against liftoff noise in Fig. 3. This is the basic cost vs noise reduction relationship that was sought. As expected, noise reduction returns, per unit increase in DOC, diminish as we move toward quieter vehicles. The curve of DOC vs cruise noise is very similar. It should be remembered that a particular proportion of cruise noise reduction has been assumed here, about 3 dB PNL in cruise for each 5 dB at liftoff. DOC at 100 miles stage length was taken as representative of typical intercity operations. DOC at other stage lengths can be found in Fig. 4.

Liftoff noise was chosen here as a measure of terminal area noise because it is independent of the takeoff path. However, it is clearly only one dimension of the terminal noise picture. Therefore, noise vs time histories of the takeoff and climbout operation were found for all vehicles as heard by observers at several distances. Figure 5 shows the histories for three helicopters as heard by an observer at 500 ft. To clarify the space-time relationships, the takeoff profiles for C75-50 and Q75-50 are plotted in Fig.

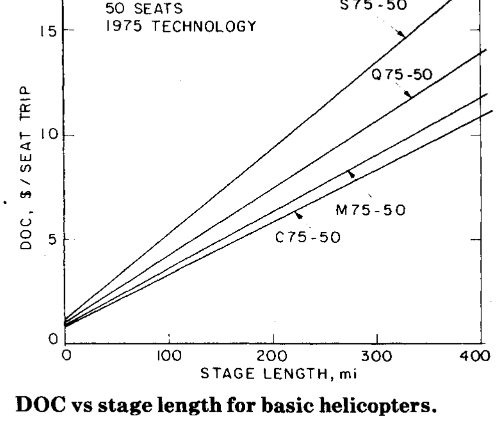

Fig. 4 DOC vs stage length for basic helicopters.

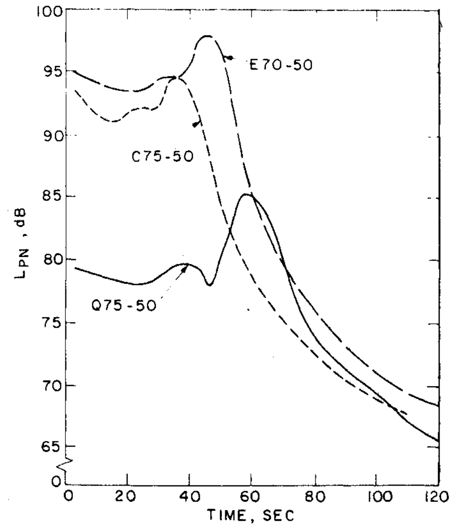

Fig. 5 Noise vs time from liftoff for 3 helicopters with observer at 500 ft.

Table 4 Parameters held constant in size and time frame variations

Parameter	C	Vehicle series M	Q	S
DL, lb/ft^2	6.0	5.0	5.0	4.0
σ	0.087	0.110	0.193	0.251
V_{cr}, mph	237	219	196	168
μ	0.50	0.55	0.60	0.60
M_{at}	0.95	0.825	0.70	0.575
$(C_T/\sigma)_{cr}$	0.070	0.065	0.055	0.050
V_{tcr}, fps	694	584	480	411
$(C_T/\sigma)_h$	0.063	0.100	0.100	0.100
V_{th}, fps	680	437	330	270

6. Notice that C75-50 moves through its profile much more rapidly, but the acceleration phase (curved portion of the profile) takes up much more space.

Size Variation

In the basic variation the payload was kept fixed at 50 seats. This was then extended by developing equivalent variations for 20, 80, and 110 seats. Table 4 contains a portion of Table 3 which was used again for the variation of noise for a given size. Keeping these parameters constant assumes that the optimal values for 50 seats are optimal for the other sizes as well. The parameters shown in Table 5 were changed along with size. Fuselage planform outlines are shown in Fig. 7. It was felt that the single rotor configuration was superior for the 20-seat size and the tandem superior for the 80 and 110 seat sizes. Both configurations were considered for the 50 seat size, and the tandem appeared very slightly but not significantly, superior.

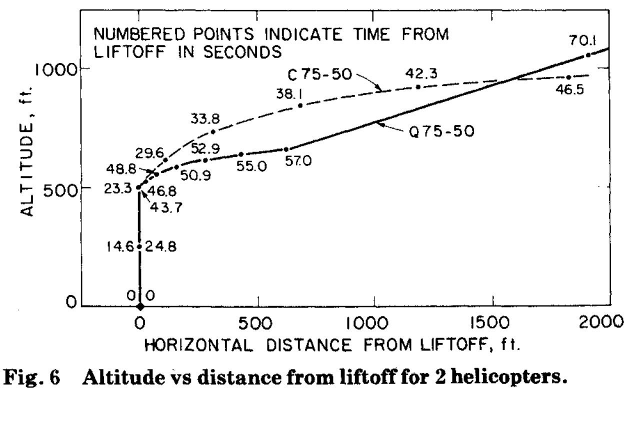

Fig. 6 Altitude vs distance from liftoff for 2 helicopters.

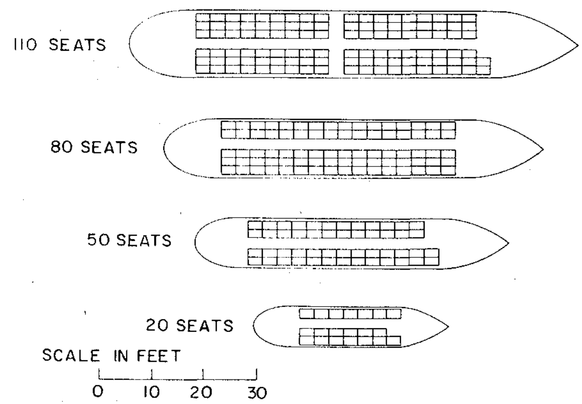

Fig. 7 Fuselage planform layouts.

Table 5 Parameters varied with size

Parameters	20	50	80	110
Flight crew	2	2	2	3
Stewardesses	1	2	2	3
Fuselage length, ft	37.6	59.8	73.0	86.2
Fuselage diameter, ft	7.8	9.4	11.0	12.6
Seats abreast	3	4	5	6
Doors	1	2	3	4
Payload weight, lb	4200	10,400	16,400	22,600
Furnishing weight, lb	1800	3650	5240	6880
Avionics and instrument weight, lb	700	840	900	1000
Main rotors	1	2	2	2
Number of engines	2	3	3	3

DOC vs liftoff noise is plotted in Fig. 8 for the various vehicle sizes. As expected, the curves have the same shape as the basic variation, with the curves for larger vehicles being lower. However, a significant result is indicated by the crossing of the 80 seat curve and the 110 seat curve the figures. These curves show that, if certain noise objectives are to be met there is an optimum aircraft size based on DOC alone. Again DOC at 100 miles stage length was chosen as representative. The DOC is plotted vs stage length in Fig. 9 for the *Q* series vehicles. These vehicles are represented by the second point from the left on the DOC vs noise curves. DOC vs stage length curves for *C*, *M*, and *S* series vehicles are very similar.

Holding the size fixed at 50 seats, the basic variation was extended along another dimension, the technology time frame. Variations equivalent to the basic variation (1975 time frame) were developed for time frames of 1970, 1980, and 1985. The parameters of Table 4 were used again for the variation of noise for a given time frame. As with the size variation, it is assumed that these parameters remain optimal, in this case for different time frames. The parameters that are varied with time frame are shown in Table 6. These parameters were derived by using engineering judgement and knowledge of specific projected technological developments to extrapolate historical trends.

DOC vs liftoff noise is plotted in Fig. 10. E70-50 is shown for added perspective. Again the curves have the same shape as the basic variation with the curves for later vehicles falling lower. It is interesting to note that the quietest 1985 vehicle costs very little more than the noisiest 1970 vehicle. In other words, the technology improvements can offset the penalties of a moderate pace of noise reduction. Again DOC at 100 miles stage length was cho-

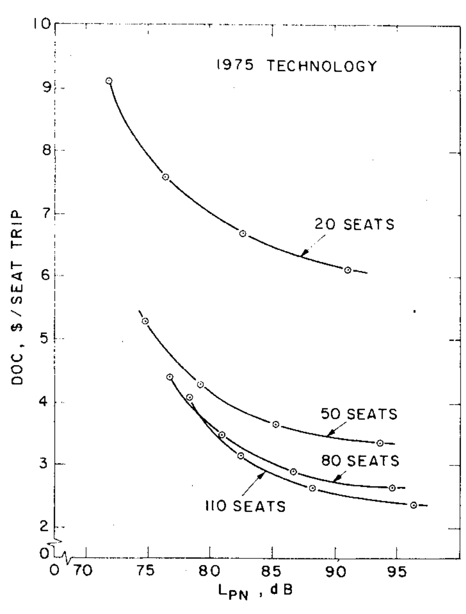

Fig. 8 DOC @ 100 mile vs liftoff noise @ 500 ft for varying size.

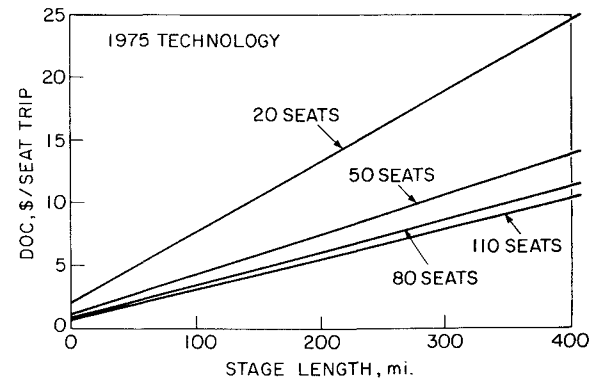

Fig. 9 DOC vs stage length for Q series helicopters and varying size.

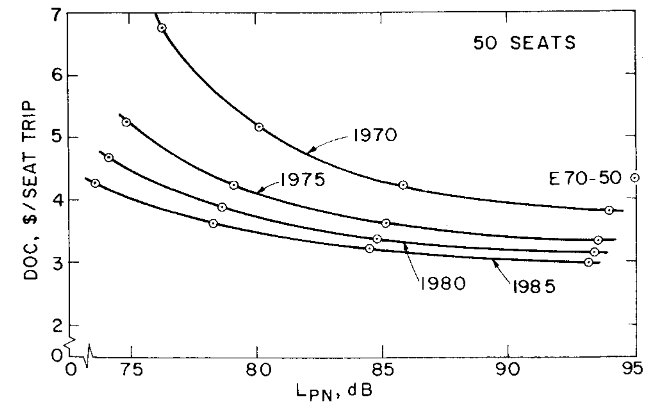

Fig. 10 DOC @ 100 mile vs liftoff noise @ 500 ft for varying time frame.

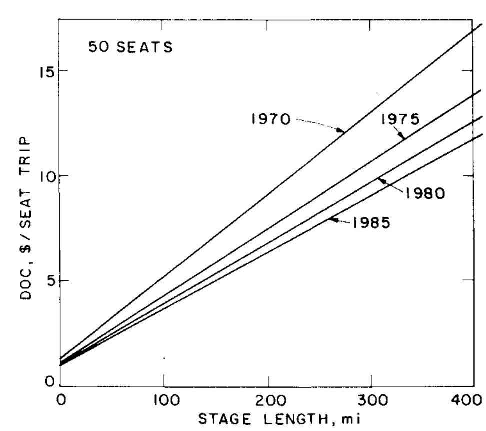

Fig. 11 DOC vs stage length for Q series helicopters and varying time frame.

Table 6 Parameters varied with time frame

Parameters	Time frame E70-50	1970	1975	1980	1985
Fuselage drag factor	3.4	3.0	2.5	2.0	1.8
Hub and pylon drag factor	0.0310	0.0250	0.0225	0.0200	0.0190
Engine power/ weight	5.0	—	—	—	—
C series	—	5.0	7.0	9.0	10.0
M series	—	4.5	6.5	8.5	9.5
Q series	—	4.0	6.0	8.0	9.0
S series	—	3.5	5.5	7.5	8.5
Specific fuel consumption	0.52	0.52	0.43	0.40	0.37
Rotor weight factor	1.20	1.05	0.90	0.80	0.70
Drive system weight factor	0.82	0.80	0.70	0.60	0.50
Fuselage weight factor	1.10	1.00	0.95	0.90	0.85

Note: The drag and weight factors multiply the appropriate formulae.

sen as representative. The DOC is plotted vs stage length in Fig. 11 for the *Q* series vehicles. DOC vs stage length curves for *C, M,* and *S* series vehicles are very similar.

Conclusions

The central conclusion of this work is that good economic performance can be expected of relatively quiet future helicopters which have low tip speeds and high solidity rotors. With a 25% increase in direct operating cost, the takeoff perceived noise level at 500 ft for a 1975, 50 passenger, 400 miles design range vehicle can be kept below 80 dB PNL. These levels are expected to be compatible with future operations from selected urban and suburban sites.

Experimental data on the noise generation and aerodynamic performance of low disk loading, high solidity rotors is needed to improve the accuracy of the noise and performance prediction techniques used here.

The expected improvements in helicopter technology over the next 15 years can offset the economic penalties due to noise reduction. Thus the direct operating cost of a very quiet 1985 vehicle can equal that of a present day vehicle designed without regard to noise.

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