CONTROL POWER REQUIREMENTS OF VTOL AIRCRAFT

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Introduction

This progress report covers the first three months of effort on NASA Grant No. NGR-05-00[illegible]-051. During this period Mr. Gary Vanderpol, a senior, developed the tilt-wing VTOL design program to be described. Mr. Peter Levin, a master's candidate, will continue this work. Mr. John Seevers, a doctoral candidate in the controls area, has begun to study the problems associated with control power requirements for the hover phase of flight as part of his doctorate thesis research.

Research Accomplished

In order to evaluate control power requirements, it is necessary to start with a representative VTOL vehicle, in this case an intercity VTOL transport. For this purpose a computer program was written to permit the rapid design of a series of VTOL aircraft of the tilt-wing type, following the philosophy of Ref. 1. The basic program inputs are the design cruise speed, altitude and range and the number of passengers. The outputs include a detailed weight breakdown, key vehicle dimensions, as well as fuel and time required in each phase of the mission. In addition, a direct operating cost (DOC) program was also written, since this is one of the better measures of the economic usefulness of a particular design.

The characteristics of the reference design are shown in Table I. It grosses about 54,000 lbs. and can carry 80 passengers over a stage length of 200 miles at cruise speeds of 400 mph at 20,000 ft. cruise altitude. It is powered by four turboprop engines with large, 12 ft. diameter propellers. The vehicle has been designed to provide a high slipstream velocity over the entire wing to prevent wing stall during the critical retransition to the vertical descent phase. The estimated DOC is also shown in Table I. The values are quite reasonable and in line with projections of other groups.

The additional power required for control purposes in the low speed flight regimes has been specified as a percentage increase in the installed power:

$$(MRP)_{TOT} = \frac{NE}{NE-1} \frac{(THP)_{HOV}}{\eta_P \, \eta_{TR}} (CPF)$$

where MRP is the maximum rated power, NE is the number of engines, (THP)HOV is the thrust horsepower required in hover, η_P and η_{TR} are the propeller and transmission efficiencies, respectively and (CPF) is the control power factor. For the reference design this was somewhat arbitrarily specified as 1.15 to give us a starting point for sensitivity analyses. This simple way of expressing the control power requirement allows us to evaluate the effect of various "control power" levels on aircraft gross weight and DOC. (Note: this use of the term control power here is strictly for convenience; in this context it means only the excess installed power for control purposes.)

Initial results of such a study are shown in Tables II and III for CPF's of 1.05 and 1.25. A new VTOL aircraft was designed for each value of CPF but with all other specifications held constant. It is interesting to note that for a five-fold increase in control power (from 5% to 25% of MRP), the vehicle gross weight increased by less than 4%. Thus it appears that this type of tilt-wing VTOL aircraft is not as sensitive to the level of control power specified as certain types of jet-powered VTOL designs.[2]

A more meaningful measure of the penalty paid for additional installed power for a commercial vehicle is the DOC. As shown in Table II, the flight operations cost and depreciation costs each increased about 9% for the five-fold increase in control power.

The maintenance costs appear to decrease almost 40% as the engine power is increased. This is due to the use of the multi-regression formula for maintenance costs developed in Ref. 3 which has a negative coefficient on the engine power term. The more conventional ATA formula which predicts increasing maintenance costs with engine power level seems more reasonable in this particular case.

In any event the total DOC will increase no more than 9% for a five-fold increase in control power. The implications of these results will be explored more fully, but the initial impression is that large increases in installed power for control purposes result in relatively small economic penalties compared to the increased safety in the low speed flight regimes (assuming, of course, that the added power is utilized effectively).

REFERENCES

1. M.I.T. Rpt. FT-66-1, Nov. 1966.
2. Schaeffler, J., Alscher, H. and Steinmetz, G., "Control-Power Usage for Maneuvering in Hover of the VJ-101 Aircraft," J. Aircraft, 4, 5, p 445-451.
3. M.I.T. Rpt. FT-66-2, Nov. 1966.

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DESIGN PROJECT INPUT DATA

PILOT SALARY	35000.00	DOLLARS/YEAR
COPILOT SALARY	21000.00	DOLLARS/YEAR
PILOT AND COPILOT FLIGHT TIME	960.00	HOURS/YEAR
FLEET SIZE	12	AIRCRAFT
AVERAGE AIRCRAFT AGE	36.00	MONTHS
DEPRECIATION TIME	12.00	YEARS
TIME BETWEEN OVERHAUL - ENGINES	4000.00	FLIGHT HOURS
VEHICLE UTILIZATION	3000.00	HOURS/YEAR
ENGINE COST	300.00	DOLLARS/LB
ELECTRONIC EQUIPMENT COST	150000.00	DOLLARS
NUMBER OF SEATS ABREST	6	
NUMBER OF DOORS	2	
NUMBER OF TOILETS	1	
NUMBER OF CREW MEMBERS	3	
SPECIFIC FUEL CONSUMPTION - NRP	0.55	LBS OF FUEL/HP HR
PROPELLER TIP MACH NUMBER	0.75	
PROPELLER ASPECT RATIO	15.00	
PROPELLER EFFIENCY	0.90	
TRANSMISSION EFFIENCY	0.90	
THICKNESS TO CHORD RATIO - WING	0.10	
OSWALD WING EFFECT FACTOR	0.70	
AIR DENSITY - SEA LEVEL STANDARD DAY	0.0023769	SLUGS/CU. FT.
AIR TEMPERATURE - SEA LEVEL STANDARD DAY	519.00	DEG. RANKINE
AIR TEMPERATURE - SEA LEVEL HOT DAY	550.00	DEG. RANKINE
KINEMATIC VISCOSITY OF AIR - S.L. HOT DAY	0.00015723	SQ. FT./SEC
STRUCTURAL LOAD FACTOR	4.50	
CRUISE VELOCITY	400.00	MPH
HEAD WIND VELOCITY	15.00	MPH

NOTES

1) AIRCRAFT ASSUMED TO BE OPERATING ON A HOT DAY
2) TOTAL GROSS WEIGHT INCLUDES FUEL
3) ENGINES ASSUMED TO DELIVER 7.5 HP PER LB
4) WEIGHT OF RESERVE FUEL NOT CONSIDERED IN DIRECT OPERATING COSTS
5) RESERVE TIME NOT CONSIDERED IN TOTAL TIME FOR CALCULATING BLOCK SPEED
6) VEHICLE WILL CLIMB AT A LIFT COEFFICIENT OF 0.5
7) IN CRUISE VEHICLE MUST FLY AGAINST A HEAD WIND

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REFERENCE DESIGN

AVAILABLE CONTROL POWER = 15.0 PERCENT
OF REQUIRED THRUST HORSEPOWER

COMPONENT WEIGHTS - LBS

FUSELAGE	6556.63
WING	5068.45
ENPENNAGE	1351.69
ENGINES	2823.26
PROPELLERS	3339.42
NACELLES	1411.63
ENGINE OIL	140.00
UNDERCARRIAGE	1622.03
TRANSMISSION	2186.50
FURNISHINGS	3750.00
AIR CONDITIONING	1540.00
HYDRALICS	571.65
ELECTRICAL EQUIPMENT	645.57
ELECTRONIC EQUIPMENT	642.00
FLIGHT CONTROLS	1081.35
FUEL TANKS	200.14
PAYLOAD	16000.00
CREW	600.00
TOTAL GROSS WEIGHT	54000.07

WING DIMENSIONS

SPAN	49.06	FT
MEAN CHORD	5.16	FT
TAPER RATIO	0.50	
MEAN SWEEPBACK ANGLE	0.00	DEG
ASPECT RATIO	9.50	
WING LOADING	213.11	LBS/SQ.FT.
WING AREA	253.39	SQ.FT.

FUSELAGE DIMENSIONS

TOTAL LENGTH	77.13	FT
DIAMETER	12.57	FT
NUMBER OF PASSENGERS	80	
NUMBER OF SEATS ABREST	6	

ENGINE SPECIFICATIONS

NORMAL RATED POWER	17645.40	HP
MAXIMUM RATED POWER	21174.47	HP
NUMBER OF ENGINES	4	
PROPELLER SOLIDITY	0.25	
PROPELLER DIAMETER	11.59	FT

CLIMB PHASE

RATE OF CLIMB	34.90	FT/SEC
VELOCITY OF CLIMB	715.24	FT/SEC

CRUISE PHASE

LIFT/DRAG	10.79
LIFT COEFFICIENT	0.97
PARASITIC DRAG COEFFICIENT	0.045
INDUCED DRAG COEFFICIENT	0.045

DESCENT PHASE

RATE OF DESCENT	74.12	FT/SEC
VELOCITY OF DESCENT	591.33	FT/SEC

TABLE OF PERFORMANCE

PHASE	FUEL - LBS	RANGE - MI	TIME - MIN
1	97.05	0.00	0.60
2	14.52	0.00	0.10
3	113.22	0.00	0.70
4	1428.99	71.72	8.83
6	1347.06	100.43	15.94
7	168.21	27.73	4.16
8	115.01	0.00	1.00
9	12.66	0.00	0.10
10	1173.01	0.00	20.00
TOTALS	4469.74 LBS	199.88 MI	51.44 MIN

DIRECT OPERATING COSTS

STAGE LENGTHS (ST. MILES)	200.00
CRUISE ALTITUDE (FEET)	20000.00
FUEL BURNED (LBS)	3298.35
BLOCK SPEED (MPH)	381.50

FLIGHT OPERATIONS (CENTS/MILE)

PILOT	9.56
COPILOT	5.73
FUEL	27.91
OIL	0.01
INSURANCE	3.96
PUBLIC LIABILITY	0.87
TOTAL (CENTS/MILE)	48.04

MAINTENANCE (CENTS/MILE)

TOTAL DIRECT	12.84
APPLIED BURDEN	4.50
TOTAL (CENTS/MILE)	17.34

DEPRECIATION (CENTS/MILE)

AIRCRAFT	21.06
ENGINES	5.24
ELECTRONICS	2.62
AIRFRAME SPARES	2.11
ENGINE SPARES	3.93
TOTAL (CENTS/MILE)	34.96

TOTAL DIRECT OPERATING COSTS

CENTS/MILE	100.34
DOLLARS/BLOCK HOUR	382.80
CENTS/AVERAGE SEAT MILE	1.57

REFERENCE DESIGN

AVAILABLE CONTROL POWER = 5.0 PERCENT OF REQUIRED THRUST HORSEPOWER

COMPONENT WEIGHTS - LBS

FUSELAGE	6537.74
WING	4957.58
ENPENNAGE	1325.95
ENGINES	2529.00
PROPELLERS	3266.29
NACELLES	1264.50
ENGINE OIL	140.00
UNDERCARRIAGE	1591.14
TRANSMISSION	2150.12
FURNISHINGS	3750.00
AIR CONDITIONING	1540.00
HYDRALICS	557.75
ELECTRICAL EQUIPMENT	638.78
ELECTRONIC EQUIPMENT	642.00
FLIGHT CONTROLS	1060.76
FUEL TANKS	188.92
PAYLOAD	16000.00
CREW	600.00
TOTAL GROSS WEIGHT	52959.78

WING DIMENSIONS

SPAN	48.40	FT
MEAN CHORD	5.10	FT
TAPER RATIO	0.50	
MEAN SWEEPBACK ANGLE	0.00	DEG
ASPECT RATIO	9.50	
WING LOADING	214.75	LBS/SQ.FT.
WING AREA	246.61	SQ.FT.

FUSELAGE DIMENSIONS

TOTAL LENGTH	77.13	FT
DIAMETER	12.57	FT
NUMBER OF PASSENGERS	80	
NUMBER OF SEATS ABREST	6	

DIRECT OPERATING COSTS

STAGE LENGTHS (ST. MILES)	200.00
CRUISE ALTITUDE (FEET)	20000.00
FUEL BURNED (LBS)	3057.46
BLOCK SPEED (MPH)	383.37

FLIGHT OPERATIONS (CENTS/MILE)

PILOT	9.51
COPILOT	5.71
FUEL	25.87
OIL	0.01
INSURANCE	3.91
PUBLIC LIABILITY	0.87
TOTAL (CENTS/MILE)	45.87

MAINTENANCE (CENTS/MILE)

TOTAL DIRECT	17.17
APPLIED BURDEN	6.01
TOTAL (CENTS/MILE)	23.17

DEPRECIATION (CENTS/MILE)

AIRCRAFT	20.75
ENGINES	4.67
ELECTRONICS	2.61
AIRFRAME SPARES	2.07
ENGINE SPARES	3.50
TOTAL (CENTS/MILE)	33.61

TOTAL DIRECT OPERATING COSTS

CENTS/MILE	102.65
DOLLARS/BLOCK HOUR	393.53
CENTS/AVERAGE SEAT MILE	1.60

REFERENCE DESIGN

AVAILABLE CONTROL POWER = 25.0 PERCENT
OF REQUIRED THRUST HORSEPOWER

COMPONENT WEIGHTS - LBS

FUSELAGE	6575.63
WING	5182.14
ENPENNAGE	1378.02
ENGINES	3128.12
PROPELLERS	3414.63
NACELLES	1564.06
ENGINE OIL	140.00
UNDERCARRIAGE	1653.63
TRANSMISSION	2223.86
FURNISHINGS	3750.00
AIR CONDITIONING	1540.00
HYDRALICS	585.94
ELECTRICAL EQUIPMENT	652.45
ELECTRONIC EQUIPMENT	642.00
FLIGHT CONTROLS	1102.42
FUEL TANKS	211.31
PAYLOAD	16000.00
CREW	600.00
TOTAL GROSS WEIGHT	55063.48

WING DIMENSIONS

SPAN	49.74	FT
MEAN CHORD	5.24	FT
TAPER RATIO	0.50	
MEAN SWEEPBACK ANGLE	0.00	DEG
ASPECT RATIO	9.50	
WING LOADING	211.47	LBS/SQ.FT.
WING AREA	260.39	SQ.FT.

FUSELAGE DIMENSIONS

TOTAL LENGTH	77.13	FT
DIAMETER	12.57	FT
NUMBER OF PASSENGERS	80	
NUMBER OF SEATS ABREST	6	

DIRECT OPERATING COSTS

STAGE LENGTHS (ST. MILES)	200.00
CRUISE ALTITUDE (FEET)	20000.00
FUEL BURNED (LBS)	3[illegible]37.99
BLOCK SPEED (MPH)	379.83

FLIGHT OPERATIONS (CENTS/MILE)

PILOT	9.60
COPILOT	5.76
FUEL	29.94
OIL	0.01
INSURANCE	4.02
PUBLIC LIABILITY	0.87
TOTAL (CENTS/MILE)	50.19

MAINTENANCE (CENTS/MILE)

TOTAL DIRECT	10.25
APPLIED BURDEN	3.59
TOTAL (CENTS/MILE)	13.84

DEPRECIATION (CENTS/MILE)

AIRCRAFT	21.37
ENGINES	5.83
ELECTRONICS	2.63
AIRFRAME SPARES	2.14
ENGINE SPARES	4.38
TOTAL (CENTS/MILE)	36.35

TOTAL DIRECT OPERATING COSTS

CENTS/MILE	100.38
DOLLARS/BLOCK HOUR	381.26
CENTS/AVERAGE SEAT MILE	1.57