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SECURITY CLASSIFICATION Open

SUBJECT The Stability of Fan-In-Wing VTOL Aircraft (From the Power-Plant Aspect)

PREPARED BY H.S. Fowler

ISSUED TO

THIS MEMORANDUM IS ISSUED TO FURNISH INFORMATION IN ADVANCE OF A REPORT. IT IS PRELIMINARY IN CHARACTER, HAS NOT RECEIVED THE CAREFUL EDITING OF A REPORT, AND IS SUBJECT TO REVIEW.

TABLE OF CONTENTS

		Page
	LIST OF ILLUSTRATIONS	3
	SUMMARY	4
1.0	INTRODUCTION	5
2.0	STABILITY IN ROLL WHILE HOVERING	5
3.0	ALTITUDE STABILITY IN HOVER	7

LIST OF ILLUSTRATIONS

	Figure
Layout of Aircraft "A" (Low Aspect Ratio)	1
Layout of Aircraft "B" (Swept High Aspect Ratio)	2
12" Fan Characteristics	3
12" Fan Deceleration Characteristic	4

SUMMARY

The stability is considered during hovering flight of a 20,000 lbs. AUW aircraft as described by Galitzine with structure weights estimated on a basis described in a memo by Pocock. In the rolling stability case, a modified form of the aircraft with a high aspect ratio wing is compared with this low-aspect ratio design.

Fan control and response rates in hovering vertical stability ("heave") are discussed briefly, and the requirements in roll stabilization are examined, together with the merits of some possible control systems.

1.0 INTRODUCTION

In view of the state now reached in the design of fan-in-wing VTOL powerplants, it is necessary to investigate the rapidity of response to control required in the engine in order to manoeuver and to hover in a stable manner. Consideration of safety during a take-off and landing also brings the reliability and power of control systems into question.

A very preliminary discussion of the subject is presented here, with a few typical calculations to give some sense of the magnitudes in question.

2.0 STABILITY IN ROLL WHILE HOVERING

The point considered is that during take-off or landing the aircraft is in effect hovering, supported entirely by the lift of its several fans, and without the normal aerodynamic controls (rudder, elevators, ailerons) used in forward flight. Its stability against gusts or uneven power distribution between the fans is therefore derived from its inertia and from some form of thrust-producing controls mounted at wing tips and tail, or in other strategic places. This role could also be filled by some of the main lifting fans. Probably the most severe destabilizing influence is the failure of a lifting fan.

Aircraft "A" and "B" will be analyzed, to find the disturbing forces due to fan failures, and the implications of these in terms of control requirements. Aircraft "A", (Figure 1), as described in Galitzine's memo has its properties tabulated below (Table 1). Aircraft "B" (Figure 2) has the same fuselage and tail, but a high aspect ratio swept wing, and a different fan arrangement. The weights of the various parts of the aircraft are estimated from known powerplant designs, and from aircraft data given by Pocock.

Table 1 - Properties of Aircraft "A" and "B"

Quantity	"A"	"B"
Span	36'	52'
Length	54'	54'
Gross Wing area	400 sq.ft.	400 sq.ft.
A.U.W.	20,000 lbs.	20,000 lbs.
Power - Propulsion	8 jet engines, 16000 HP	8 jet engines, 16000 HP
- Lift	8 fans 3' d. 30,000 lbs	8 fans 3' d. 30,000 lbs

The weight breakdown of the aircraft is given below. The only weight difference between "A" and "B" lay in the wing. By simple geometry, using dimensions scaled from the drawing, the unit inertias for various parts were calculated, and combined to find the mass inertias of the two aircraft in roll. Their inertias were of course different, since the engines and wings had different radii of gyration about the fuselage centreline in the two cases.

In the initial stages of a roll, it was considered that the aerodynamic inertia was small (less than 1% of the mass inertia) and could therefore be neglected in the present estimate.

Table 2 - Weight Breakdown - Aircraft "A" and "B"

AUW	=		20,000 lbs.
Payload	=		5,000 lbs.
Powerplant	=	8 x 475 =	3,800 lbs.
Structure	=	33% AUW =	6,600 lbs.
Fuel (in wing centre section)	=		4,600 lbs.
			20,000

Of the Structure Weight: 6,600 lbs.

The components are:	"A"	"B"
Wing (with ailerons)	2,450	2,500
Tail (with controls)	960	930
Fuselage	2,400	2,380
Undercarriage	790	790
	6,600	6,600

Of the Engine/Fan Weight: 3,800 lbs.

The components are: $\frac{3800}{8}$ = 475 lbs.

Gas generator/Jet engine = 140 lbs.
Turbofan unit = 230 lbs.
Jet pipe and valve = 105 lbs.
475 lbs.

Hence, moment of inertia of aircraft in roll:

Aircraft "A" - = 882,940 lbs.ft.^{2}

Aircraft "B" - = 1,532,040 lbs.ft.^{2}

In the case of Aircraft "A", assume that an outboard fan (fan A) fails, while the opposite outboard fan "H" keeps running, with the aircraft hovering so that each fan is supplying $\frac{20000}{8}$ = 2500 lbs. lift. We therefore have the unbalanced lift of fan H producing a rolling moment, M = 2500 x 12.5' = 31200 lbs.ft. In the aircraft of Moment of Inertia = 882,940, this produces a rolling acceleration of:

$$\frac{6 \times 307.1 \times 31200}{882,940} = 65°/\text{sec./sec.}$$

Assume similarly that an inboard fan (D) fails, producing a moment of 2500 x 6.5' = 16300 lbs.ft. This will produce a rolling acceleration of 34°/sec./sec.

If the aircraft were climbing at the time, rather than merely hovering, the fans would be at higher output, and the unbalanced lift, and hence rolling acceleration, due to a failure would be higher. In the design under discussion it might reach a value of 97°/sec./sec. if the fans were at maximum rated lift when one failed.

In the case of Aircraft "B", corresponding analysis shows that the failure of an outboard fan (A) would produce a rolling acceleration of 65°/sec./sec. (It is purely coincidental that rearrangement of wing and powerplant weights, and fan moment arms should combine to give the same acceleration as before). An inboard fan failure (fan D) would in this case give a rolling acceleration of 20°/sec./sec.

3.0 ALTITUDE STABILITY IN HOVER

While the aircraft is hovering it will be disturbed vertically by gusts, and will need changes in lift to stabilize it vertically. It is also necessary to specify some minimum time to alter lift to change from hover to climb or descent at any given rate.

Let us require a vertical acceleration of

10 ft./sec./sec. (approximately 1/3 g)

If the aircraft described above (A or B), while hovering each fan will be producing 2500 lbs. of lift. The aircraft mass depending on this fan will therefore be 2500 lbs. Therefore to produce an acceleration of 10 ft./sec./sec. in this case, a force of $\frac{2500 \times 10}{32.2}$ = 775 lbs. of extra thrust is required from each fan. This is a 30% increase of thrust. From test results on the 12" fan rig, this would mean a 25% increase of RPM (see Figure 3).

To a first approximation, we therefore need to find the time taken to change the fan RPM by 25%, while operating at about 80% thrust, in order to estimate the time to develop the required 10 ft./sec./sec. vertical acceleration.

During accelerations or decelerations, four sets of forces act on the rotor; the driving torque, the inertia, the aerodynamic drag, and the bearing friction which is small.

During an acceleration, the rate of speed increase is proportional to the torque applied, less the effects of inertia and aerodynamic drag.

During a deceleration, the rate of speed decrease is proportional to the sum of the reduction of driving torque and aerodynamic drag.

The configuration of the 12" fan rig is very different from that of the 36" fan, with its tip-turbine. Calculations would enable the inertias of the two arrangements to be compared, but it would be very difficult to compare the aerodynamic drag of the two arrangements. For this reason, it is not felt advisable to make any further strict analysis at this stage. However, as a first step, a brief test on the 12" fan showed that when the power air supply was cut off sharply by the emergency trip, the deceleration, recorded by a Brush pen recorder, was as shown in Figure 4. This indicated a deceleration of the order of 13000 RPM/sec. in the 4000-zero RPM range. Preliminary calculations suggested that the full-sized (36" d.) turbofan would have an inertia some 600 times that of the 12" dia. fan, shaft, and turbine, assembly tested here.

In the low speed range, the aerodynamic drag term will be small compared with the inertia term and in this very elementary analysis will be neglected. Thus, if deceleration of 12" fan = 12800 RPM/sec. and inertia (36" unit) = 600 x inertia (12" unit), we may say that neglecting air drag

$$\text{Deceleration of 36" unit} = \frac{12800}{600} = 21.0 \text{ RPM/sec.}$$

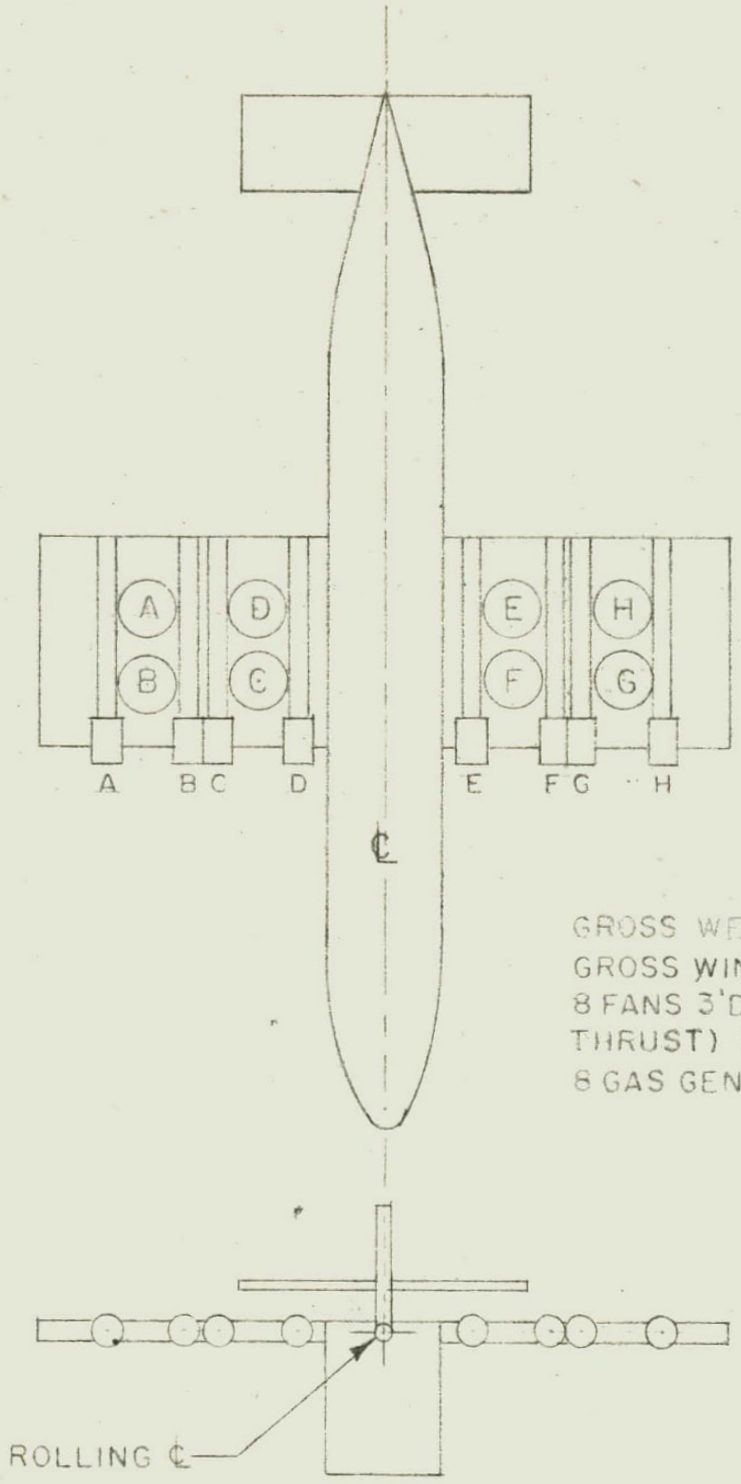
in the low speed region.

Thus from 1500 RPM to zero, the 36" unit should need a run down time of $\frac{1500}{21.0}$ = 72 secs. Early runs of the 36" unit show a run down time of 80 secs. from 1500 RPM to zero. This suggests that the figures quoted above, although extremely tentative, are at least a reasonable guide until more accurate values are obtainable.

Assuming this correlation between the 12" and 36" fans to hold, to a very rough approximation, we may then return to the higher reaches of the curve, and observe that to change speed 25%, from 15000 to 12000 RPM, the 12" fan will require $\left(\frac{15000 - 12000}{50000}\right)$ = .06 secs. Applying the factor of 600, this would mean a time of .06 x 600 = 36 seconds to develop the 1/3 g vertical acceleration required. This would lead to control times at least 10 times too sluggish for reasonable stability.

In effect, the times deduced above make it obvious that altitude stability and manoeuverability are not obtainable by altering the RPM of fans as at present envisaged. Serious thought should therefore be given to the problem of increasing the thrust variation rate. One obvious method is to run the fans continuously at a higher-than-hovering thrust, and continually modulate this with quick-acting spoilers. This method, which is comparable to the use of thrust spoilers during the landing approach by orthodox jet aircraft, is simple but wasteful, and other methods should be devised if possible.

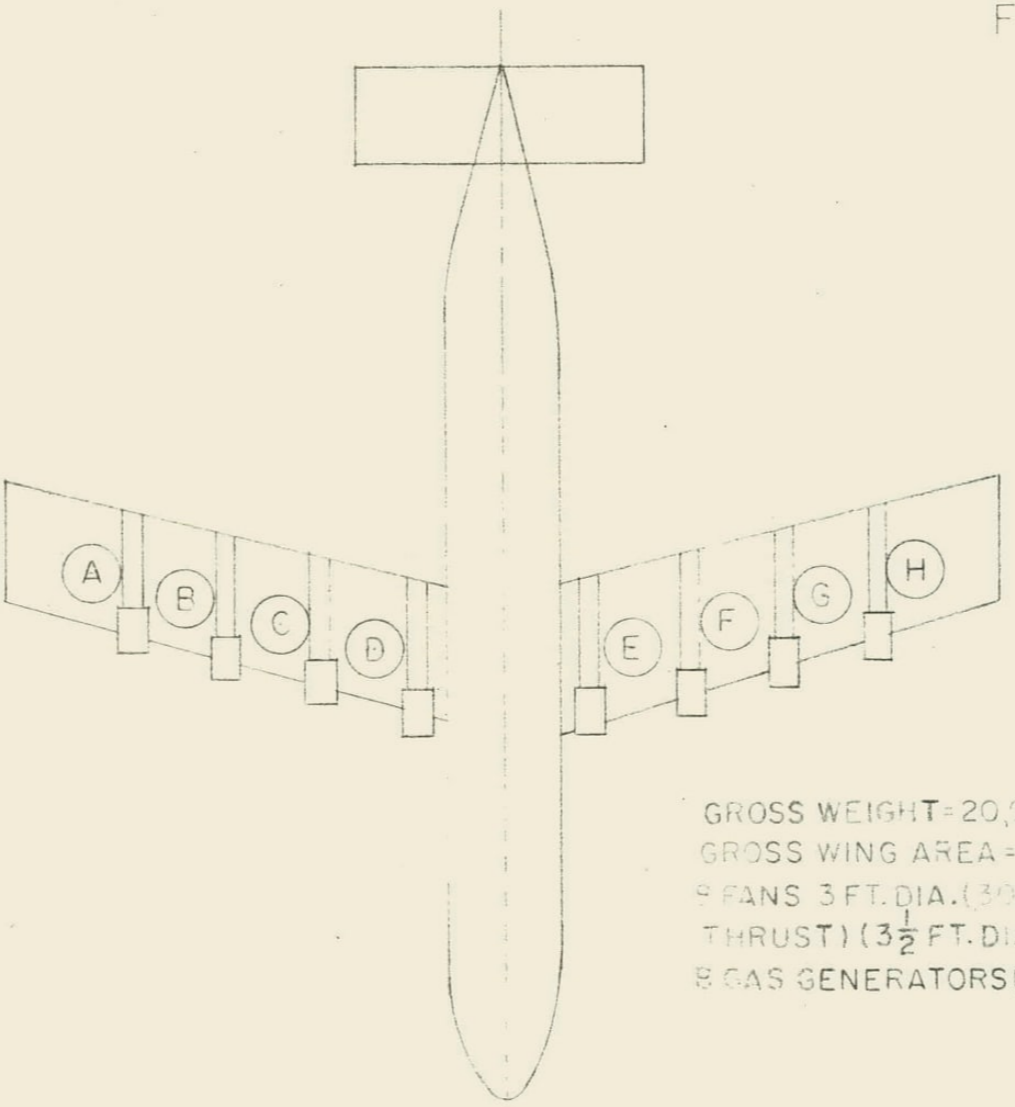
FIG. 1



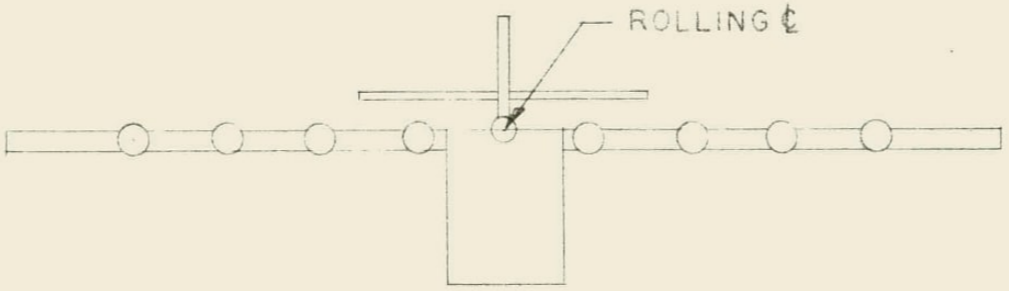
GROSS WEIGHT = 20,000 LBS.
GROSS WING AREA = 400 $FT.^2$
8 FANS 3' DIA (30,000 LBS. THRUST) ($3\frac{1}{2}$ FT DIA O/A)
8 GAS GENERATORS (16,000 HP)

AIRCRAFT 'A'
(LOW ASPECT RATIO)
SCALE — 1" = 10 FT.

FIG. 2



GROSS WEIGHT = 20,000 LBS
GROSS WING AREA = 400 FT^2
8 FANS 3 FT. DIA. (30,000 LBS THRUST) ($3\frac{1}{2}$ FT. DIA. O/A)
8 GAS GENERATORS (16,000 HP)



AIRCRAFT

SCALE — 1" = 10 FT.

FIG.3

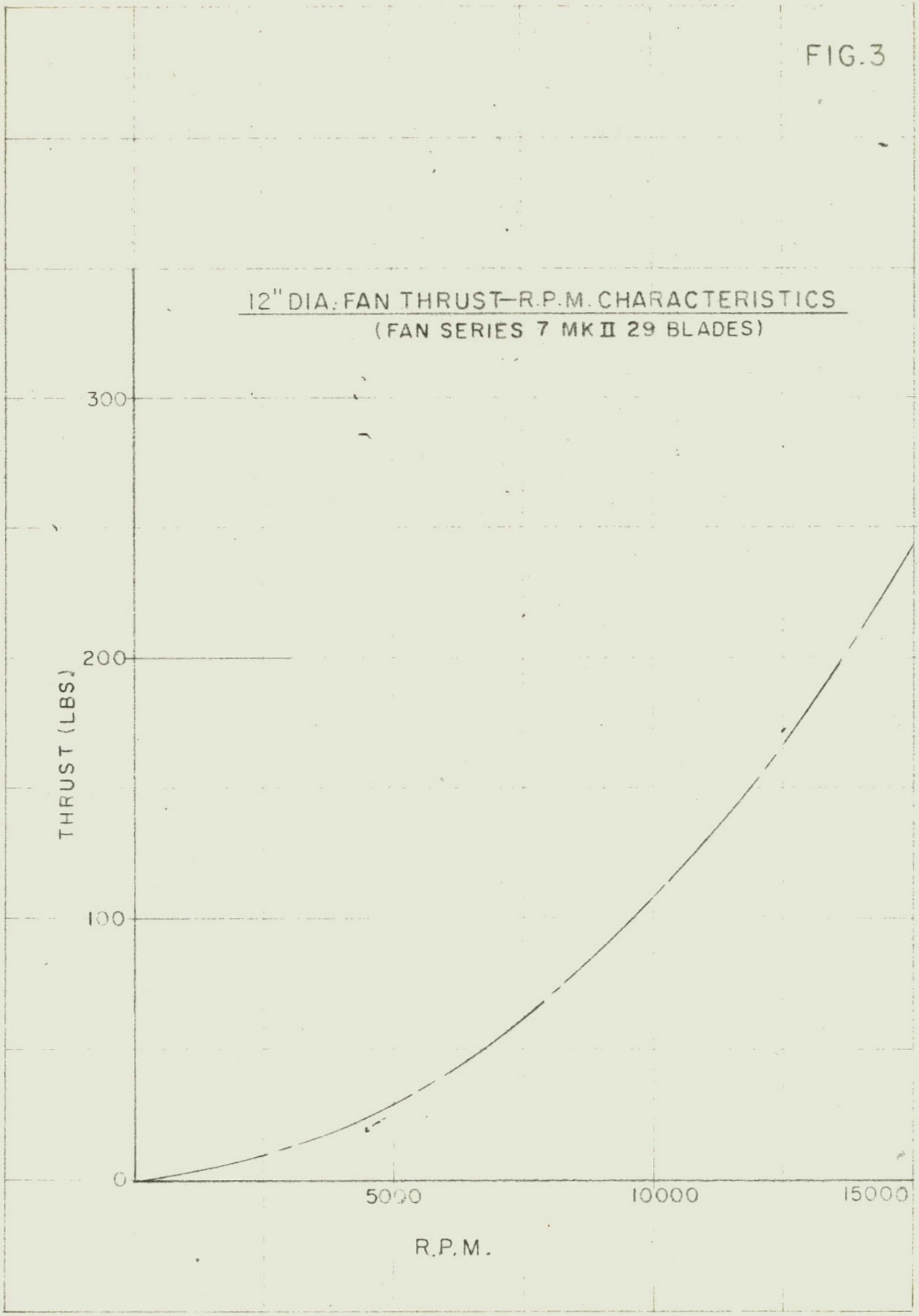
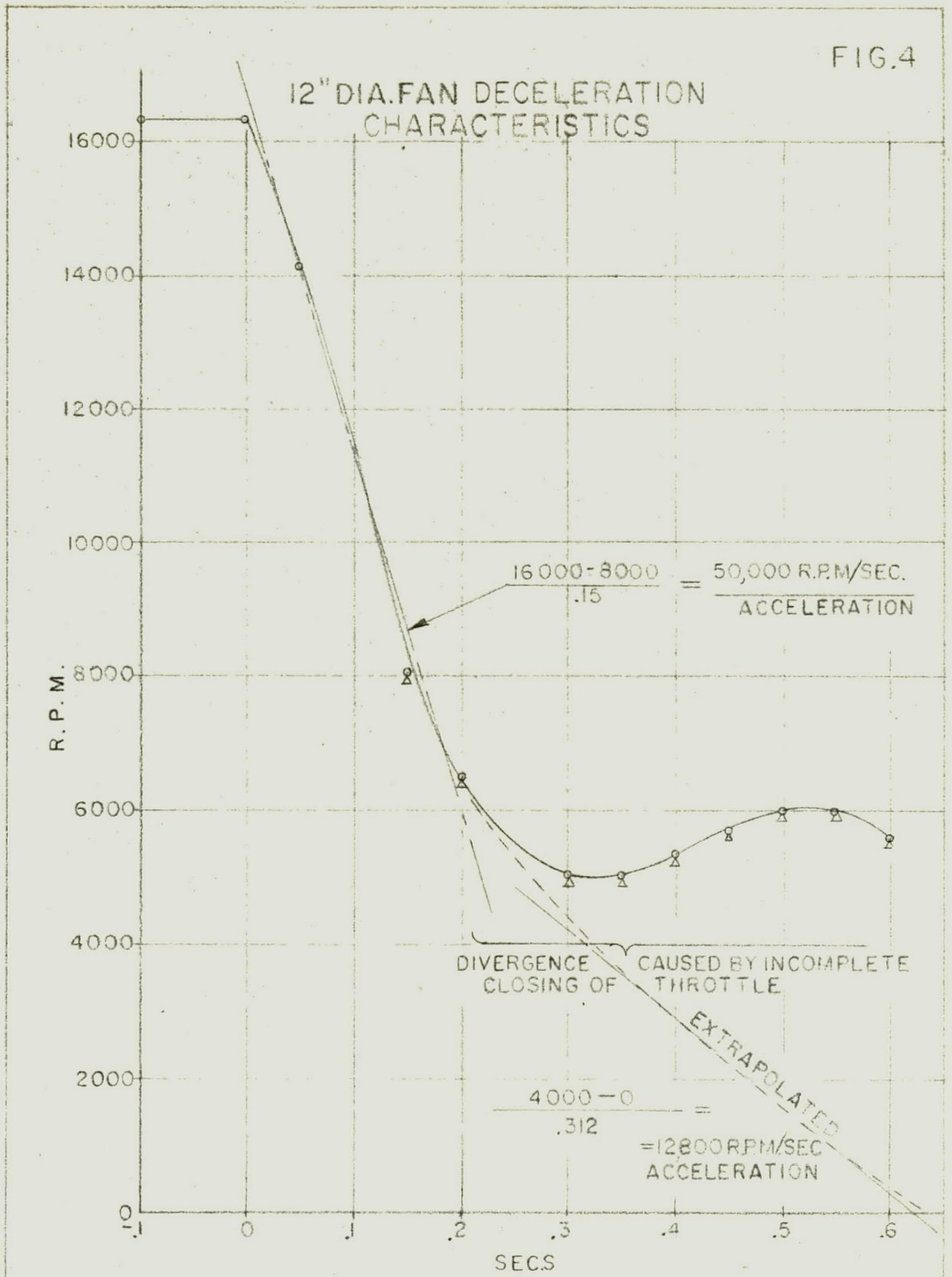

12" DIA. FAN THRUST—R.P.M. CHARACTERISTICS
(FAN SERIES 7 MK II 29 BLADES)
300
200
100
0
THRUST (LBS.)
5000
10000
15000
R.P.M.

FIG.4


12" DIA. FAN DECELERATION CHARACTERISTICS
16000
14000
12000
10000
8000
6000
4000
2000
0
R.P.M.
16000-8000 / .15 = 50,000 R.P.M/SEC. ACCELERATION
DIVERGENCE CAUSED BY INCOMPLETE CLOSING OF THROTTLE
EXTRAPOLATED
4000-0 / .312 = =12800 R.P.M/SEC ACCELERATION
-.1
0
.1
.2
.3
.4
.5
.6
SECS