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Preliminary Axial Flow Turbine Design and Off-Design Performance Analysis Methods for Rotary Wing Aircraft Engines; II-Applications

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Abstract

In this paper, preliminary studies on two turbine engine applications relevant to the tilt-rotor rotary wing aircraft are performed. The first case-study is the application of variable pitch turbine for the turbine performance improvement when operating at a substantially lower shaft speed. The calculations are made on the 75 percent speed and the 50 percent speed of operations. Our results indicate that with the use of the variable pitch turbines, a nominal (3 percent (probable) to 5 percent (hypothetical)) efficiency improvement at the 75 percent speed, and a notable (6 percent (probable) to 12 percent (hypothetical)) efficiency improvement at the 50 percent speed, without sacrificing the turbine power productions, are achievable if the technical difficulty of turning the turbine vanes and blades can be circumvented. The second case-study is the contingency turbine power generation for the tilt-rotor aircraft in the One Engine Inoperative (OEI) scenario. For this study, calculations are performed on two promising methods: throttle push and steam injection. By isolating the power turbine and limiting its air mass flow rate to be no more than the air flow intake of the take-off operation, while increasing the turbine inlet total temperature (simulating the throttle push) or increasing the air-steam mixture flow rate (simulating the steam injection condition), our results show that an amount of 30 to 45 percent extra power, to the nominal take-off power, can be generated by either of the two methods. The methods of approach, the results, and discussions of these studies are presented in this paper.

1. Introduction

The Rotary-Wing Aircraft Engines of primary interest to us are the engines for the Civil Tilt-Rotor Aircraft configurations. For the tilt-rotor aircraft engines, two outstanding operational characteristics, that are unique to the rotary-wing aircraft as opposed to the fix-wing aircraft, have been identified and investigated by the aircraft industry ((ref. 1), and (refs. 2 and 3)). The first unique characteristic is the need to operate the tilt-rotor aircraft at a variable propeller (main rotor) speed for economical engine power and fuel consumptions and for better overall aircraft performance. A preferred arrangement been identified is to operate at the 100 percent speed during take-off and at the 50 percent speed in cruise (as discussed in reference 4). With a power train transmission of fixed gear ratio, this requirement would mean that the engine power turbine needs to be operating at a 50 percent reduction in its designed rotational speed for the duration of aircraft cruise operation, which presents a challenge to the engine turbine design in terms of affordable efficiency and operability. The second outstanding requirement is the need for contingency power for the tilt-rotor aircraft in the One Engine Inoperative (OEI) scenario. The amount of additional turbine power needed for the OEI maneuvering operation is seen quoted at the 30 to 40 percent range of the take-off power (for example, in reference 2). The challenge to the turbine design is whether or not this amount of extra power can be produced without grossly over-sizing the engine.

To gain insights to these questions, the turbine off-design computer code AXOD and the validation effort invested, as that described in part 1 of the paper, are utilized. The intention is to conduct investigations at the preliminary level on the response in performance of the power turbine. To accomplish this, a representative power turbine geometry is needed, and in this work, this turbine geometry is to take the first two stages of the Low Pressure Turbine developed in the GE-E^3 Program (GE-E^3-LPT; a five-stage turbine). The reason for this decision is the following: because details of this two-stage turbine are available, it is a realistic turbine design and was tested as the Block I unit in the development stage by GE, and it has been studied and validated (see part 1 of the paper.) This paper describes the studies conducted based on this two-stage turbine geometry in addressing to the two operational challenges cited.

For clarity, the two case-studies are presented and discussed in separate sequence.

2. Variable Pitch Turbine

When operating at a substantially lower speed of rotation, performance of the given turbine degrades considerably. To quantify the severity of this performance degradation, the two-stage turbine is executed at the 100 percent, the 75 percent, and the 50 percent speeds-of-rotation over the full range of pressure ratios (starting from a pressure ratio of nearly unity, sweeping all the way to the pressure ratio of the last-blade-row-choke) using AXOD. The overall total efficiencies and the overall turbine power productions (in HP: horse power) are obtained as the baseline performances of the standard geometry turbine. These results are plotted against the overall total-to-static pressure ratios, as illustrated by figures 1 and 2.

2.1. Performances Under the Standard Turbine Geometry

Shown by the plots, when operating at the 75 percent speed, the efficiency of the turbine degrades as much as 7 percentage points in the high pressure ratio regime, compared to the performance at the 100 percent speed; and when operating at the 50 percent speed, this efficiency degradation has escalated to as much as 20 percentage points.

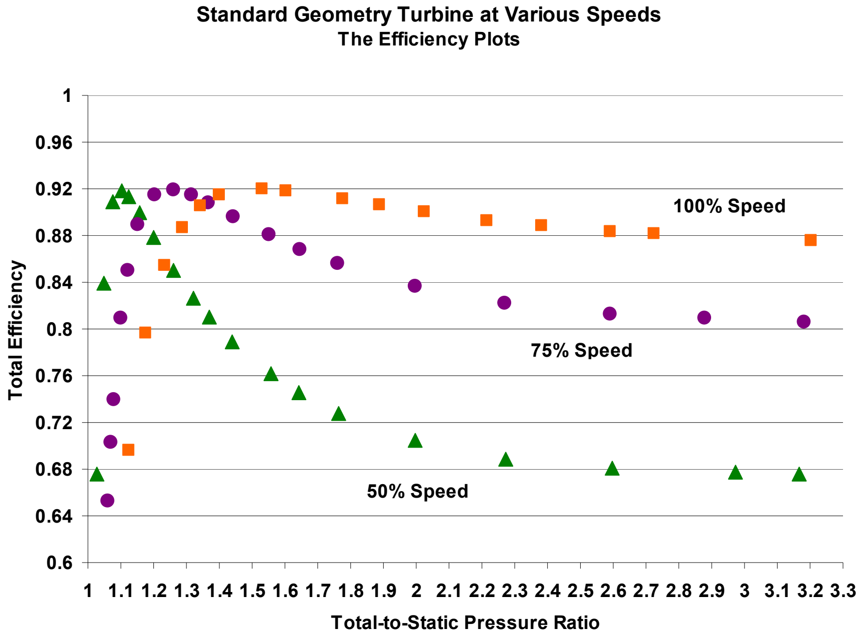

Figure 1.—Efficiencies of the Standard Geometry Turbine at Various Speeds.

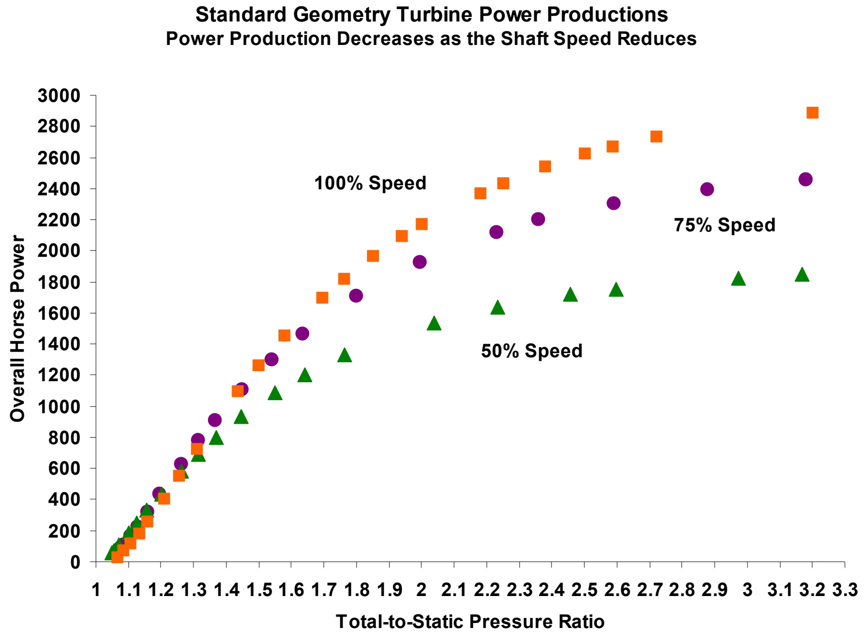

Figure 2.—Power Productions of the Standard Geometry Turbine at Various Speeds.

The power productions also show a considerable amount of decrease at the high pressure ratio regime when operating at the lower rotational speeds. However, a desirable design goal for the tilt-rotor aircraft is to utilize this power reduction of the power turbine at the lower shaft speed to achieve and maintain the desired cruising speed of the aircraft, in which the turbine power and the shaft speed need not be so high as that required for the take-off where the engine full power and the 100 percent shaft speed are necessary. Thus this power reduction from the power turbine needs not be a deficiency as long as the power production at the lower speed meets the power requirement of the aircraft operation. And shown by figure 2, the power produced at the 50 percent speed is at least (in the high pressure ratio zone) 65 percent of the full power produced at the 100 percent speed, thus this decrease in power at the lower shaft speed would cause no concern.

To understand and explain the efficiency degradation at the lower speeds, some relevant performance indicators are tabulated in table 1. These performance indicators are obtained at a single-point operation (under various shaft speeds), where the turbine inlet conditions are chosen to be the same as the design-point conditions of this turbine. These conditions are the scaled conditions (to the true operating conditions of the full scale turbine) applied in the turbine design process and in the follow-on rig testing of the turbine-built. As a reference, these conditions are listed here:

$$P_t^{in} = 3.1026 * 10^5 \, N/m^2 = 45 \, \text{psia} \tag{1}$$

$$T_t^{in} = 416.67 \, {}^\circ K = 750 \, {}^\circ \text{R} \tag{2}$$

$$\omega^{in} = 28.386 \text{ kg/s} = 62.58 \text{ lbm/s} \tag{3}$$

And the 100 percent speed-of-rotation of the shaft is:

$$\Omega^{100\%} = 3209 \text{ rpm} \tag{4}$$

TABLE I.—PERFORMANCE INDICATORS OF THE STANDARD TURBINE OPERATING AT VARIOUS SPEEDS

	100 percent speed	75 percent speed	50 percent speed
Work factor (Stage 1)	3.424	4.843	7.691
Work factor (Stage 2)	3.201	4.226	6.424
Stage 1 reaction (P)	0.3351	0.2814	0.2202
Stage 1 reaction (R)	0.2170	0.1674	0.1154
Stage 2 reaction (P)	0.3457	0.2805	0.2113
Stage 2 reaction (R)	0.1979	0.1336	0.0771
Incidence (Stator 1; deg.)	3.443	3.443	3.443
Incidence (Rotor 1; deg.)	4.823	9.859	14.023
Incidence (Stator 2; deg.)	5.550	10.492	14.768
Incidence (Rotor 2; deg.)	6.488	11.105	15.386
T-to-S P.R. (Overall)	2.01	1.77	1.60

The last column in table 1 are the resulting overall total-to-static pressure ratios of the turbine when operating at the chosen inflow conditions of equations (1) to (3) at various speeds. They are provided as a reference, for placing these point-of-references on the performance plots of figures 1 and 2.

As that indicated by table 1, the reasons for the efficiency degradation can be summarized in three folds:

(1). The Stage Work Factors increase at the lower speed operation. The turbine becomes very highly-loaded at the 50 percent speed.

(2). The flow incidences increase as the speeds-of-rotation decrease. Highly skewed inflows are present at the 50 percent speed operation.

(3). The third reason is that the Stage Reactions also decrease to the worse as the speeds of rotation reduce. Note that in table 1 the Reaction (P) stands for the pitch-line (mean-line) reaction, and the Reaction (R) stands for the reaction occurred at the root.

An effective remedy to these problems is to employ the variable pitch turbine by rotating the vanes (probable) and the blades (hypothetical) to correct the skewness of the approaching inflows. And when done correctly, it also tends to improve the stage loadings and the stage reactions all together.

We have performed such calculations for the 50 percent speed operation and the 75 percent speed operation. The study for the 50 percent speed is presented first, followed by the study for the 75 percent speed.

2.2. Performance of the Variable Pitch Turbine at 50 Percent Speed

The vanes and the blades are turned along their axes perpendicular to the axis-of-rotation of the shaft. The goal is to reduce the inflow incidences experienced by the blade rows while maintaining the reasonable resulting stage reactions (avoiding the occurrence of a negative stage reaction). This pitch-angle (the vane/blade turning angle) adjustments are conducted at the same single-point operating conditions as that from which the performance indicators of the standard geometry turbine were obtained, which is the design-point flow conditions of this turbine as noted. The angle adjustments are done by trial-and-error. The primary judgment of satisfaction is when the efficiency-reading obtained shows the highest elevation compared to that plotted from the standard geometry turbine.

The amount of blade angle turnings determined through this trail-and-error process for the variable geometry turbine operating at the 50 percent speed, by turning the Stators-only, are listed in table 2. The resulting performance indicators are tabulated in table 3, together with the performance indicators of the 50 percent speed obtained at the Standard Geometry for the ease of comparison.

TABLE 2.—ANGLE TURNINGS DETERMINED FOR THE STATORS-ONLY VARIABLE PITCH TURBINE AT 50 PERCENT SPEED

	Stator 1	Rotor 1	Stator 2	Rotor 2
Angle turned (deg.)	+5.5	0.0	+9.0	0.0

The + sign on the stator in table 2 means turning the stator vane with its leading edge moving towards the direction of the shaft rotation.

TABLE 3.—PERFORMANCE INDICATORS OF THE STATOR-ONLY VARIABLE PITCH TURBINE AT 50 PERCENT SPEED

	50 percent speed (Standard)	50 percent speed (Stators-only)
Work factor (Stage 1)	7.691	6.467
Work factor (Stage 2)	6.424	4.535
Stage 1 reaction (P)	0.2202	0.3866
Stage 1 reaction (R)	0.1154	0.3242
Stage 2 reaction (P)	0.2113	0.4644
Stage 2 reaction (R)	0.0771	0.3986
Incidence (Stator 1; deg.)	3.443	–1.675
Incidence (Rotor 1; deg.)	14.023	6.372
Incidence (Stator 2; deg.)	14.768	5.985
Incidence (Rotor 2; deg.)	15.386	–0.307
T-to-S P.R. (Overall)	1.60	1.38

Likewise, the amount of blade angle turnings determined through trail and error for the variable geometry turbine operating at the 50 percent speed, by turning both the Stators-and-Rotors, are listed in table 4. And its resulting performance indicators are listed in table 5, together with the performance indicators of the 50 percent speed obtained at the Standard Geometry, for ease of comparison.

TABLE 4.—ANGLE TURNINGS DETERMINED FOR THE STATORS-AND-ROTORS VARIABLE PITCH TURBINE AT 50 PERCENT SPEED

	Stator 1	Rotor 1	Stator 2	Rotor 2
Angle turned (deg.)	+5.5	+5.0	+9.0	–2.8

In table 4, the + sign on the stator means turning the stator vane with its leading edge moving towards the direction of the shaft rotation. The + sign on the rotor, however, means turning the rotor blade leading edge away from (opposite to) the direction of the shaft rotation.

TABLE 5.—PERFORMANCE INDICATORS OF THE STATORS-AND-ROTORS VARIABLE PITCH TURBINE AT 50 PERCENT SPEED

	50 percent speed (Standard)	50 percent speed (Stators-Rotors)
Work factor (Stage 1)	7.691	5.518
Work factor (Stage 2)	6.424	4.921
Stage 1 reaction (P)	0.2202	0.1651
Stage 1 reaction (R)	0.1154	0.0566
Stage 2 reaction (P)	0.2113	0.5715
Stage 2 reaction (R)	0.0771	0.5255
Incidence (Stator 1; deg.)	3.443	–1.675
Incidence (Rotor 1; deg.)	14.023	1.131
Incidence (Stator 2; deg.)	14.768	–2.311
Incidence (Rotor 2; deg.)	15.386	2.227
T-to-S P.R. (Overall)	1.60	1.39

The last column in tables 3 and 5 are the resulting overall total-to-static pressure ratios of the turbines when operating at the chosen inflow conditions of equations (1) to (3) at the 50 percent speed. It is given primarily as a reference, so that these point-of-references can be located in the performance plots to follow.

One observes, from tables 3 and 5, that by turning the stators only or by turning both the stators and the rotors, all three categories of the performance indicators: Work Factors, Incidence Angles, and Stage Reactions, are improved for the better. However, precisely how much of the performance improvement is achieved has to be examined through actually calculating and plotting the performance characteristics over the full range of operating conditions. We executed AXOD in the sweeping mode for the variable pitch turbines (of both the Stator-only and the Stators-and-Rotors) operating at the 50 percent shaft speed, over the full range of pressure ratios (to the last-blade-row-choke). The results are shown in figures 3 and 4.

We have observed a maximum of 6 percentage-point efficiency improvement when only the stators are turned; and have observed a maximum of 12 percentage-point efficiency improvement, when both the stators and the rotors are turned favorably.

There is no appreciable change observed in the power productions of the turbines. However, the pressure ratio where the last-blade-row-choke occurred becomes smaller for the variable pitch turbine, more so for the Stators-and-Rotors variable pitch turbine than for the Stators-only variable pitch turbine. In order to produce the same amount of full power of the standard geometry turbine at 50 percent speed, the variable pitch turbine might have to be operating at the last blade row exit flow over-expanded, and there is a limit-load achievable under the flow over-expansion. This point will be discussed more in the next section, Contingency Turbine Power Generation. Although the limit-load of the variable pitch turbine could reach the full power (of the last-blade-row-choke) of the standard geometry turbine operating at the same speed, but it might not reach the limit-load achievable by the standard geometry turbine.

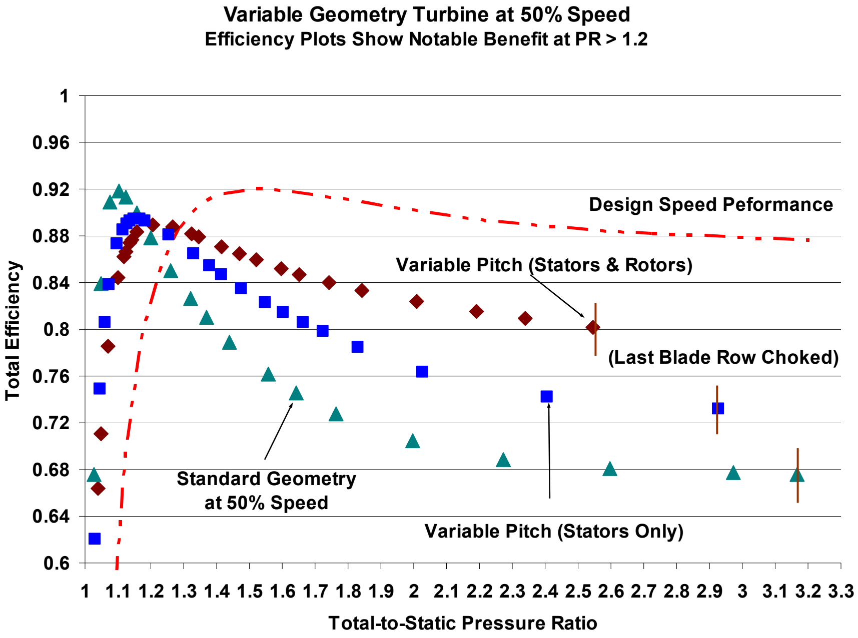

Figure 3.—Efficiencies of the Variable Pitch Turbines at 50 Percent Speed.

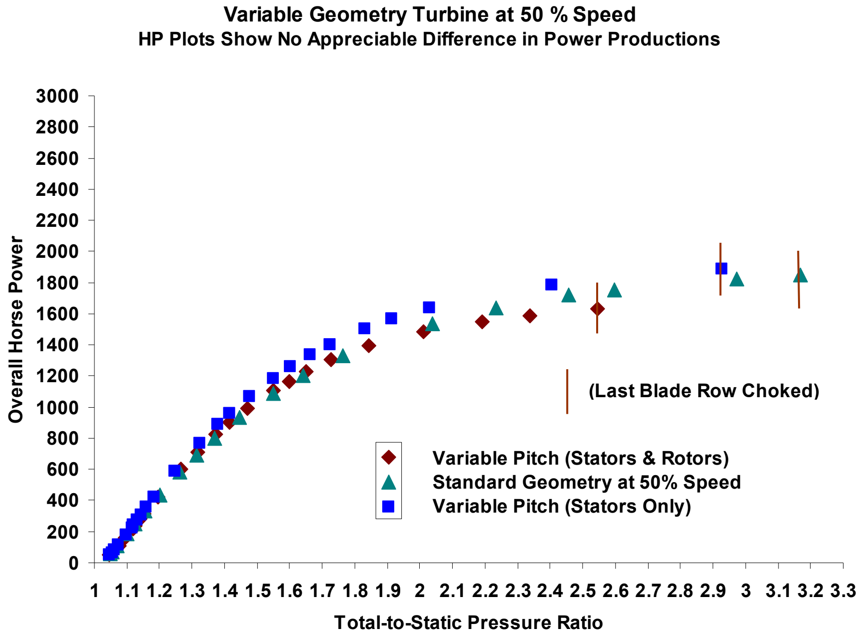

Figure 4.—Power Productions of the Variable Pitch Turbines at 50 Percent Speed.

2.3. Performance of the Variable Pitch Turbine at 75 Percent Speed

The same calculations are performed over the variable pitch turbines operating at the 75 percent speed. The amount of blade angle turnings determined through the trail-and-error process by turning the Stators-only variable pitch turbine at the 75 percent speed are listed in table 6. The resulting performance indicators are tabulated in table 7, together with the performance indicators of the 75 percent speed obtained at the Standard Geometry for the ease of comparison.

TABLE 6.—ANGLE TURNINGS DETERMINED FOR THE STATORS-ONLY VARIABLE PITCH TURBINE AT 75 PERCENT SPEED

	Stator 1	Rotor 1	Stator 2	Rotor 2
Angle turned (deg.)	+4.5	0.0	+5.0	0.0

TABLE 7.—PERFORMANCE INDICATORS OF THE STATOR-ONLY VARIABLE PITCH TURBINE AT 75 PERCENT SPEED

	75 percent speed (Standard)	75 percent speed (Stators-only)
Work factor (Stage 1)	4.843	4.133
Work factor (Stage 2)	4.226	3.235
Stage 1 reaction (P)	0.2814	0.4123
Stage 1 reaction (R)	0.1674	0.3333
Stage 2 reaction (P)	0.2805	0.4273
Stage 2 reaction (R)	0.1336	0.3226
Incidence (Stator 1; deg.)	3.443	–0.744
Incidence (Rotor 1; deg.)	9.859	1.820
Incidence (Stator 2; deg.)	10.492	5.403
Incidence (Rotor 2; deg.)	11.105	–0.638
T-to-S P.R. (Overall)	1.77	1.54

Likewise, the amount of blade angle turnings determined for the variable geometry turbine operating at the 75 percent speed, by turning both the Stators-and-Rotors, are listed in table 8. And its resulting performance indicators are listed in table 9, together with the performance indicators of the 75 percent speed obtained at the Standard Geometry, for ease of comparison.

TABLE 8.—ANGLE TURNINGS DETERMINED FOR THE STATORS-AND-ROTORS VARIABLE PITCH TURBINE AT 75 PERCENT SPEED

	Stator 1	Rotor 1	Stator 2	Rotor 2
Angle turned (deg.)	+4.5	+1.5	+5.0	–2.0

Again, the + sign on the stator means turning the stator vane with its leading edge moving towards the direction of the shaft rotation. The + sign on the rotor, however, means turning the rotor blade leading edge away from (opposite to) the direction of the shaft rotation.

TABLE 9.—PERFORMANCE INDICATORS OF THE STATORS-AND-ROTORS VARIABLE PITCH TURBINE AT 75 PERCENT SPEED

	75 percent speed (Standard)	75 percent speed (Stators-Rotors)
Work factor (Stage 1)	4.843	3.899
Work factor (Stage 2)	4.226	3.461
Stage 1 reaction (P)	0.2814	0.3494
Stage 1 reaction (R)	0.1674	0.2559
Stage 2 reaction (P)	0.2805	0.5065
Stage 2 reaction (R)	0.1336	0.4224
Incidence (Stator 1; deg.)	3.443	–0.744
Incidence (Rotor 1; deg.)	9.859	0.220
Incidence (Stator 2; deg.)	10.492	2.226
Incidence (Rotor 2; deg.)	11.105	1.174
T-to-S P.R. (Overall)	1.77	1.57

The last column in tables 7 and 9 are the resulting overall total-to-static pressure ratios of the turbines when operating at the chosen inflow conditions of equations (1) to (3) at the 75 percent speed. Again, they are provided primarily as a reference.

Again, observed from tables 7 and 9, that by turning the stators only or by turning both the stators and the rotors, all three categories of the performance indicators: Work Factors, Incidence Angles, and Stage Reactions, are improved for the better.

The performances of the variable pitch turbines (of both the Stator-only and the Stators-and-Rotors) at 75 percent speed, over the full range of pressure ratios (to the last-blade-row-choke), are calculated and plotted in figures 5 and 6.

In the 75 percent speed case, we have observed a maximum of 3 percentage-point efficiency improvement when only the stators are turned; and have observed a maximum of 5 percentage-point efficiency improvement, when both the stators and the rotors are turned favorably.

Again, at the 75 percent speed, there is no appreciable change in the power productions of the turbines observed. And similar to the result of the 50 percent speed, the pressure ratio where the last-blade-row-choke occurred also has receded to a smaller value for the variable pitch turbine, more so for the Stators-and-Rotors variable pitch turbine than for the Stators-only variable pitch turbine. And as noted, this is a concern to the maximum power (the limit-load) achievable by the variable pitch turbine, which could be smaller than that achievable by the standard geometry turbine.

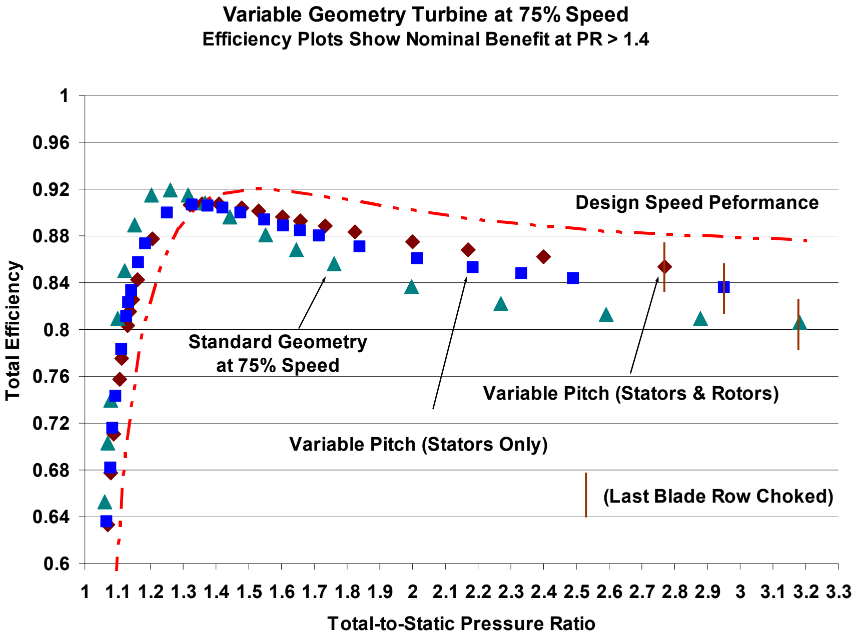

Figure 5.—Efficiencies of the Variable Pitch Turbines at 75 Percent Speed.

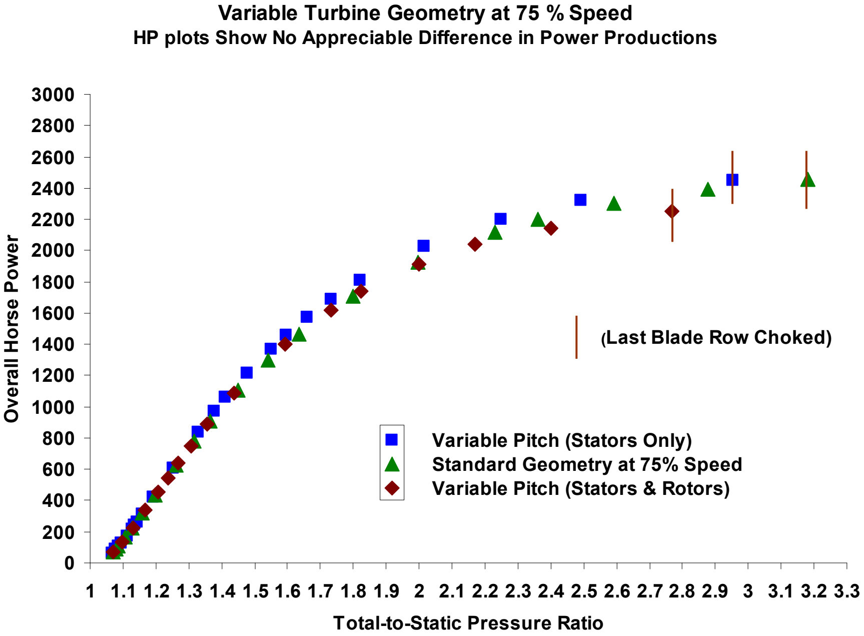

Figure 6.—Power Productions of the Variable Pitch Turbines at 75 Percent Speed.

2.4. Concluding Remarks for the Variable Pitch Turbines

The variable pitch turbine is seen to improve the efficiency of the standard turbine operating at the substantially lower speed of rotation. The calculations performed indicate that a maximum of 3 percentage-point efficiency improvement when only the stators were turned, and a maximum of 5 percentage-point efficiency improvement when both the stators and the rotors were turned, are achievable when operating at the 75 percent shaft speed. And at the 50 percent shaft speed, a maximum of

6 percentage-point efficiency improvement when only the stators were turned, and a maximum of 12 percentage-point efficiency improvement when both the stators and the rotors were turned, were obtained. The power productions of the variable pitch turbines do not change appreciably when compared to the power production of the standard turbine operating at the same speed, but the pressure ratio where the last-blade-row-choke occurred does recede to a lower value. This may cause concern of the limit-load achievable by the variable pitch turbine.

The calculations performed were at the preliminary level. There are a few important physical phenomena not accounted for in the analysis. These include the change in the tip clearance leakage flow effect, the change in the coolant flow effect, the tip-clearance management, the coolant flow management, etc; and not the least is the change in the detailed flow physics itself across the blade rows when the vanes and blades of a turbine are turned. Results presented here should be regarded as a reference view of the performance improvement achievable by the variable pitch turbines. Furthermore, the technical difficulties to accomplish the turnings of the vanes and blades of a turbine were not been considered. Current engine technology could accomplish the turnings of the stators of a turbine, but is unlikely to be able to turn the rotors at all. The performance improvement observed on the Stators-only variable pitch turbines are to be regarded as ‘probable’, the performance improvement observed on the Stators-and-Rotors variable pitch turbines are strictly ‘hypothetical’ at the current technology readiness level.

3. Contingency Turbine Power Generation

As stated in the introduction, there is the need for contingency turbine power for the tilt-rotor aircraft operating in the One Engine Inoperative (OEI) scenario. The amount of additional turbine power needed in the OEI maneuvering operation is seen quoted at the 30 to 40 percent range of the take-off power in reference. 2. The purpose of this study is to see whether or not this amount of extra turbine power can be generated without resorting to over-sizing the engine.

This is a rather complicated topic, and in here we are conducting a preliminary level of study over the performance of the power turbine only. For the analysis to be reasonably close to the actual engine operation, and to be comparatively objective, certain ground rules and assumptions would have to be made. These are:

1. The air flow intake to the engine cannot increase indefinitely but should have a limiting value at the engine full throttle. This value is designated here to be the air mass-flow-rate at the design point of the engine. The speed of rotation of the power turbine required in the contingency power production period of the OEI operation is designated here to be the 100 percent speed, the same as that required for the operation at take-off.
2. The power turbine is un-cooled, i.e., there is no coolant flow added directly into the power turbine.
3. Fuel mass and the fraction-of-weight of its thermal properties are small compared to those of the air flow, thus the fuel-air mixture is replaceable by just the air. Effect of the extra fuel burn would simply be an increase in the air temperature to the turbine stages.
4. The High Pressure Turbine (HPT) will not choke ahead of the Power Turbine (This assumption could be stringent. However, it is necessary since in this study we are analyzing the power turbine alone in isolation. In reality the HPT could choke ahead of the power turbine, which would bring additional complication to the problem, and that is beyond the scope of the current study).

The power production of the power turbine under the engine full throttle can be augmented via two (conventional) methods: throttle push, or, steam injection, as seen suggested in references 2 and 3. The condition of operation of each method considered in this work is further defined here as the following:

a. Throttle Push

The air flow intake reaches its limiting value at the full throttle. The fuel burn is increased. This will lead to a total temperature increase at the Power Turbine inlet, while the total pressure is assumed unchanged. The turbine power is augmented through the increase in the total temperature. The air flow to turbine will not exceed its limiting value, instead, it could decrease due to the flow choking in the flow path of the Power Turbine, thus would limit the amount of power augmentation achievable.

b. Steam Injection

Again, the air flow has reached its limiting value at the engine full throttle, and the fuel burn is increased. Steam (water vapor) is injected into the burner and the HPT (at upstream to the Power Turbine), such that the total temperature at the Power Turbine inlet is assumed to remain unchanged (no increase in the inlet total temperature or the total pressure.) The turbine power is augmented through the increase in the amount of total mass flow rate (of the air-steam mixture) provided. The flow again could choke in the flow path of the Power Turbine, thus would limit the amount of power augmentation achievable, since the amount of mixture mass-flow-rate allowed through would be limited by the choking.

The turbine model applied in this work, as noted previously, is the first two stages of the Low Pressure Turbine developed in the GE-E^3 program (GE-E^3-LPT; a 5-stage turbine). The design-point operating conditions of this turbine are given by equations (1) to (4). Note particularly, that the design-point air mass-flow-rate for this turbine is 62.58 lbm/s, which is the limiting value of the air flow enforced in the study. The off-design computer code AXOD is applied, executing primarily at the single-point operating mode with the inlet mass flow rate (pure air for the throttle push, and air-steam mixture for the steam injection method) being explicitly assigned through input.

3.1. Throttle Push

The inlet total temperature of the Power Turbine is increased from 750 °R (the initial limiting state) to 900 °R with a constant increment of 25 °R. The total pressure at the turbine inlet is fixed at 45 psia. The air mass-flow-rate at the turbine inlet was enforced at 62.58 lbm/s, until the inlet total temperature reached 825 °R (i.e., Tt_in/Tt_ref = 1.1), where choking in the flow path occurred. Since then, the air flow mass allowed through (determined by manually adjusting the input value of the air mass-flow-rate to an amount where the choke point is nearly reached) has decreased almost linearly with respect to the increase in the inlet total temperature (flow velocity limiting; as the temperature goes higher the density decreases, but the flow speed is limited by choking, thus the mass flow rate would go down.). Figure 7 shows this result.

The mass flow rate obtained and the resulting overall total-to-static pressure ratio at each point-of-operation examined through this process (of up to the condition of near-choke) are tabulated in table 10.

TABLE 10.—THE MASS FLOW RATES AND THE RESULTING PRESSURE RATIOS OF THE POINTS EXAMINED IN THROTTLE PUSH

Tt_in/Tt_ref	ω_in (lbm/s)	Total-to-Static P.R.
1.0	62.58	2.01
1.0333	62.58	2.16
1.0667	62.58	2.42
1.1	62.171	3.06
1.1333	61.321	3.06
1.1667	60.504	3.05
1.2	59.719	3.05

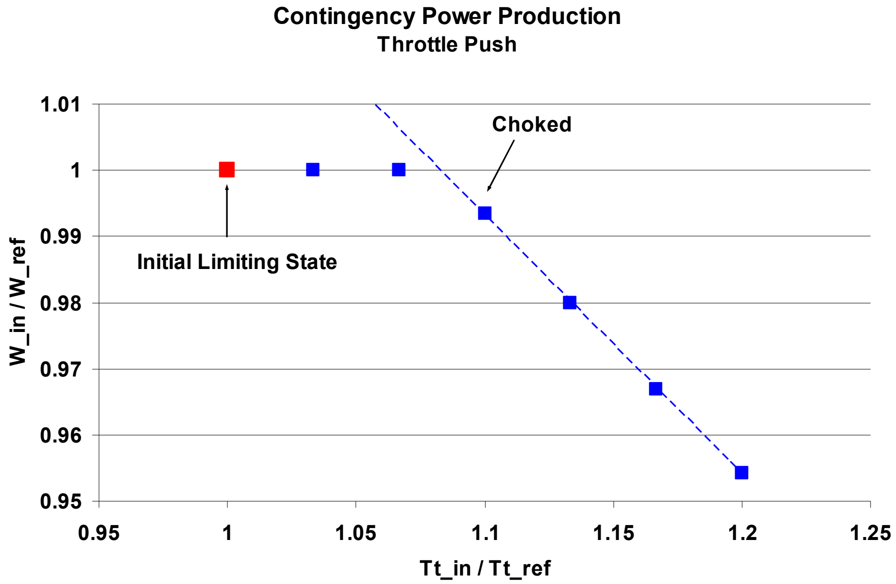

Figure 7.—Mass Flow Rate Limitations in Throttle Push.

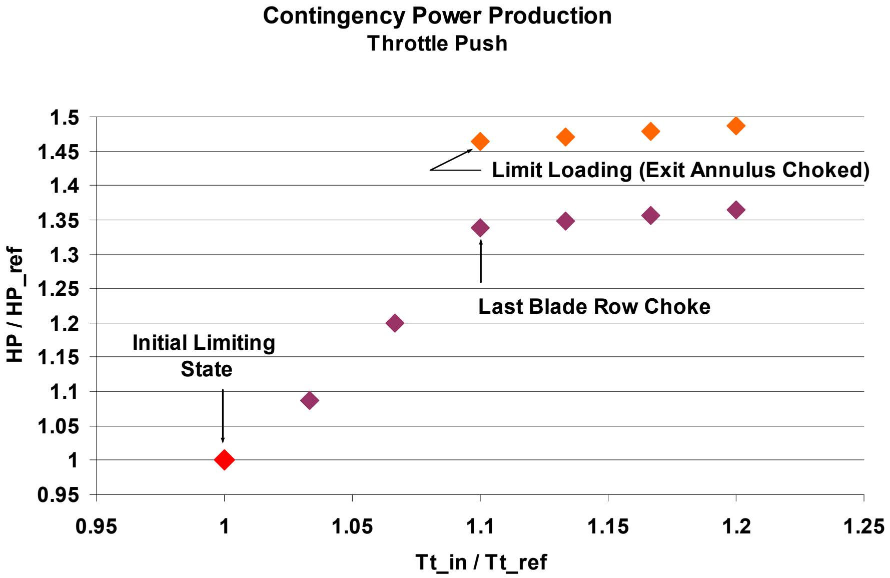

Figure 8.—Turbine Power Productions in Throttle Push.

The corresponding overall turbine power production is shown in figure 8. The power production initially increases quadraticly before choke, but turns to nearly constant after the choking in the flow path occurs. In figure 8, there are two levels of the choked-flow power production trends. The one marked 'Last Blade Row Choke' means the power produced by the turbine is obtained at the onset of the last-blade-row-choke. The exit flow at the last blade row (a rotor) is not in over-expansion. This power is, of course, not the maximum amount of power obtainable from the choked turbine, because the exit flow of the last-blade-row-choke can be over expanded, and additional power production from the turbine can be extracted. This extra power production from the choked-flow over-expansion will reach a limiting value, known as the limit-load, as the annulus region of the last blade row exit has reached the choke point also. The limit-loads at each of the choked-flow total temperatures are shown in figure 8, marked as the 'Limit Loading (Exit Annulus Choked)'. The achievable turbine power will be somewhere in between the two trends, depends on how low the exit static pressure can be (how much choked-flow over-expansion can have). The limit-load is obtained by executing AXOD in the sweeping mode, utilizing its powerful choke-iteration algorithm, while specifying the termination point of the code execution to be when the last-annulus-choke is reached. The limit-load is read from the result at the termination point.

The overall total-to-static pressure ratio at the limit loading condition and the resulting through-flow mass obtained are tabulated in table 11, for comparison to the near-choke conditions tabulated in table 10.

It is noted here, that the turbine power-extract under the choked-flow over-expansion actually remains rather flat before the last-annulus-choke, over a fairly wide range of pressure ratios. The maximum turbine power is achievable at a pressure ratio much less than the pressure ratio of the last-annulus-choke.

TABLE 11.—THE OVERALL PRESSURE RATIOS AT THE LIMIT-LOADING CONDITION AND THE RESULTING MASS FLOW RATES OBTAINED IN THROTTLE PUSH

Tt_in/Tt_ref	ω_in (lbm/s)	Total-to-Static P.R.
1.0	-------	------
1.0333	-------	------
1.0667	-------	------
1.1	62.173	8.58
1.1333	61.325	8.73
1.1667	60.509	8.72
1.2	59.720	8.70

As indicated by figure 8, an amount of 35 to 45 percent extra power can be generated by throttle push, in comparison to the power generated at the initial-liming-state which, in this work, represents the power production at the nominal take-off condition under the engine full throttle.

3.2. Steam Injection

In this study, calculations are made with the inlet total temperature and the inlet total pressure both remain unchanged at the design-point values (750 °R for the total temperature and 45 psia for the total pressure). The air mass-flow-rate to the turbine is enforced at the constant level of 62.58 lbm/s while the steam (water vapor) is added into the air stream of the turbine inlet incrementally, with a constant steam-to-air mass ratio of 1 percent per increment. Choking in the flow path occurred when 3 percent or more (6 percent is the maximum amount calculated) steam-to-air mass ratio is added. At the choked-flow, the mass flow rate of the steam-air mixture allowed through is obtained through manually adjusting the total mixture mass-flow-rate specified at the turbine inlet, until the near-choke point is reached. Figure 9 shows this result. A note-worthy point is that the mixture mass-flow-rate allowed through after the initial choking occurred has also decreased almost linearly. The reason for this is because the density of the steam (water vapor) is lighter than the density of the air at the same temperature and pressure, thus when the steam injection rate goes up, the mixture density goes down. Since the mass flow rate is the density times the choked-flow velocity, and the choked-flow velocity does not very much in all the choked cases (steam-to-air mass ratio greater than 3 percent), therefore the through flow mass would decrease as the result.

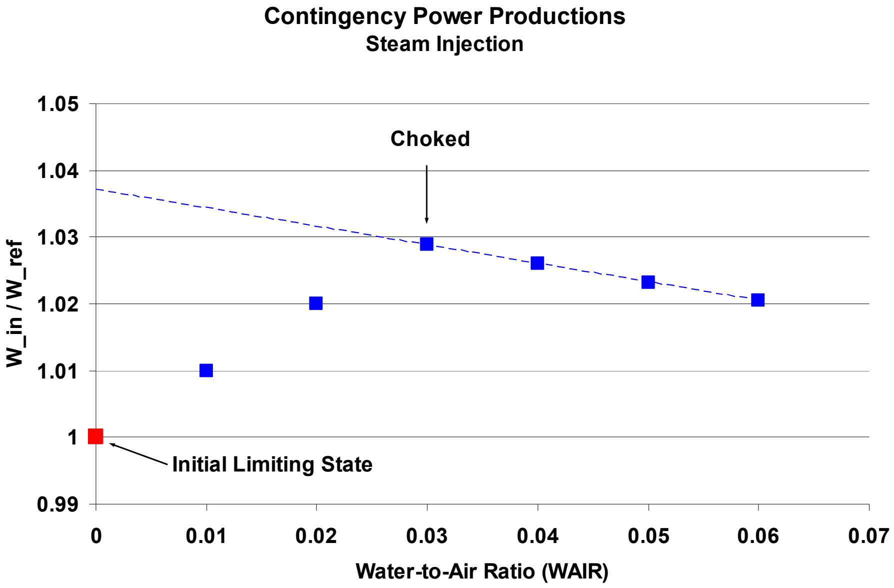

Figure 9.—Mass Flow Rate Limitations in the Steam Injection Method.

The mixture mass flow rate and the resulting overall total-to-static pressure ratio of each point-of-operation examined by this process are tabulated in table 12.

TABLE 12.—THE MIXTURE MASS FLOW RATE AND THE RESULTING PRESSURE RATIO AT THE POINTS EXAMINED IN STEAM INJECTION

Water-to-Air Ratio, percent	ω_in (lbm/s)	Total-to-Static P.R.
0.0	62.58	2.01
1.0	63.206	2.14
2.0	63.832	2.34
3.0	64.382	3.07
4.0	64.204	3.07
5.0	64.030	3.06
6.0	63.862	3.06

The corresponding overall turbine power production is shown in figure 10. The power production again increases quadraticly before choke, but turns to nearly constant after choking occurs. Again, in figure 10, two levels of choked-flow power production trends are shown. The one marked ‘Last Blade Row Choke’ means the power produced by the turbine is obtained at the onset of the last-blade-row-choke. At this point, the exit flow of the last blade row is not over-expanded. The one marked as the ‘Limit Loading (Exit Annulus Choked)’ is the power produced at the maximum choked-flow over-expansion, known as the limit-load.

The overall total-to-static pressure ratio at the limit-loading condition and the resulting mixture mass flow rate allowed through are tabulated in table 13, for comparison to the near-choke conditions tabulated in table 12. Again it is noted, that the maximum turbine power can be achieved at a pressure ratio much less than the pressure ratio of the last-annulus-choke, because the turbine power-extract under the choked-flow over-expansion actually remains rather flat before the last-annulus-choke, over a fairly wide range of pressure ratios.

The results of figure 10 indicate that an amount of 30 to 45 percent extra power (again, depending on how low the exit static pressure can be), in comparison to the power generated at the initial-liming-state (which, as noted, represents the nominal take-off power generated by the turbine) can be produced by the steam injection method.

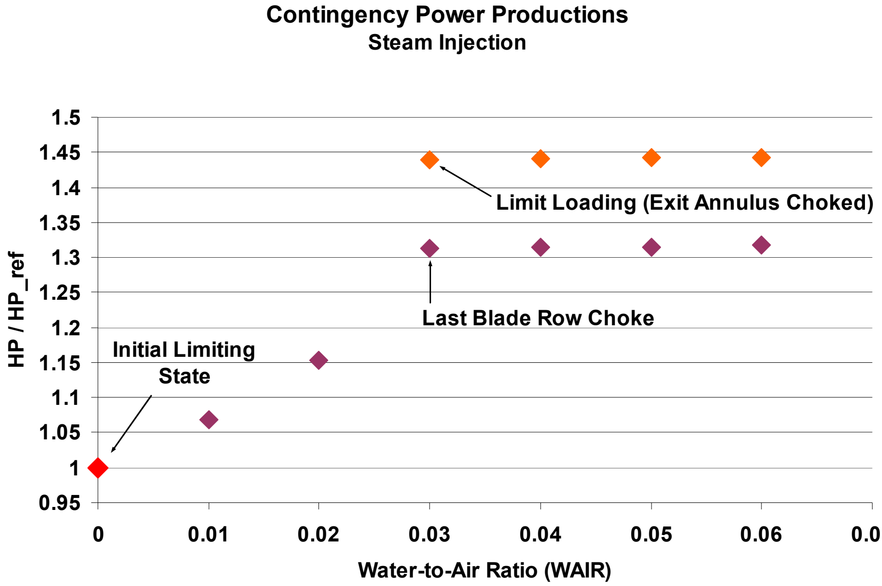

Figure 10.—Turbine Power Productions in the Steam Injection Method.

TABLE 13.—THE OVERALL PRESSURE RATIOS AT THE LIMIT-LOADING CONDITION AND THE RESULTING MIXTURE MASS FLOW RATES OBTAINED IN STEAM INJECTION

Water-to-Air Ratio, Percent	ω_in (lbm/s)	Total-to-Static P.R.
0.0	-------	------
1.0	-------	------
2.0	-------	------
3.0	64.387	8.61
4.0	64.208	8.61
5.0	64.035	8.60
6.0	63.867	8.60

3.3. Concluding Remarks for the Contingency Turbine Power Generation

An amount of 30 to 45 percent extra turbine power, to the nominal take-off power, is shown to obtainable by either of the two methods studied: throttle push or steam injection. If the last blade row exit flow is not over-expanded, the extra power achievable is 35 percent for the throttle push and 30 percent for the steam injection scheme; when operating at the choked-flow over-expansion, the maximum amount of extra power produced can reach 45 percent by either of the two methods. These results indicate that the requirement for the tilt-rotor aircraft contingency turbine power generation of 30 to 40 percent extra to the nominal take-off power can be met by either the throttle push or the steam injection method, without resorting to engine over-sizing.

Nevertheless, each method has its drawbacks and concerns. Specifically, the throttle-push could lead to turbine over-heating as indicated by figure 8, that a minimum of 10 percent turbine inlet total temperature increase is needed when operating at the choked-flow expansion. And thus in the throttle-push, elaborated turbine cooling scheme would be required in order to reduce the turbine wall temperature and wall heat flux during the contingency power production while avoiding the negative impact from excessive cooling, particularly when operating at its normal condition where high level of turbine cooling is not needed (discussed in reference 2). The steam injection method, on the other hand, has to carry an additional weight of water onboard the aircraft, which is a dead-weight penalty to pay. As to how much of the extra weight of water is needed can be estimated from figure 11.

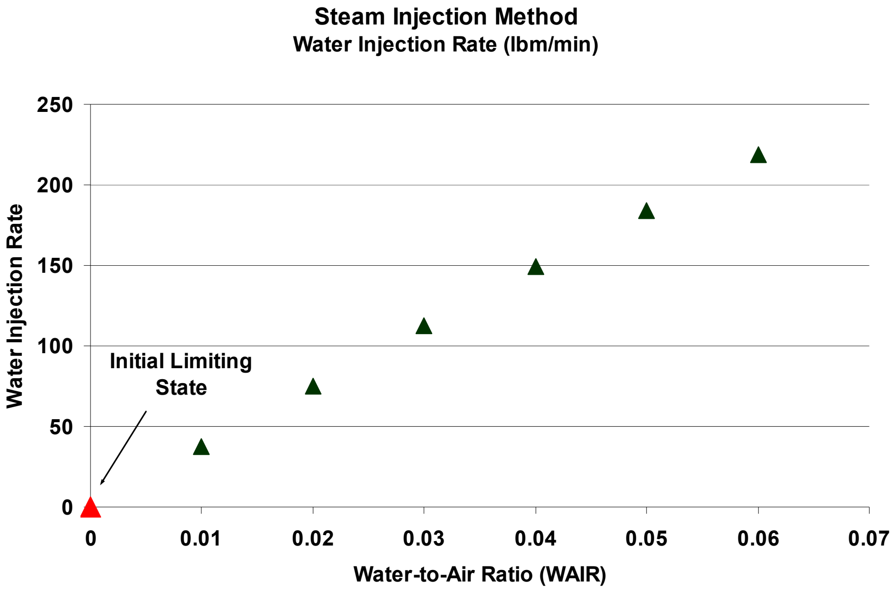

Figure 11.—The Weight of Water Required in the Steam Injection Method.

The actual weight of water required depends on what is the targeted water injection rate, and depends on how long it is needed in the OEI maneuvering operation. The length of time where the contingency power is needed in the OEI maneuvering is seen specified as a two-and-a-half-minute operation (ref. 3). At the 3 percent steam-to-air mass ratio, that would translate into 275 lb of water carried onboard for this particular turbine configuration.

4. Summary

Two case-studies were performed in this paper. In regard to the variable pitch turbine for performance improvement when operating at a substantially lower shaft speed, our calculations indicate that a maximum of 3 percentage-point efficiency improvement when only the stators were turned, and a maximum of 5 percentage-point efficiency improvement when both the stators and the rotors were turned, are achievable at the 75 percent speed. At the 50 percent speed, a maximum of 6 percentage-point efficiency improvement when only the stators were turned, and a maximum of 12 percentage-point efficiency improvement when both the stators and the rotors were turned, were obtained. The power productions of the variable pitch turbines do not change appreciably when compared to the power production of the standard turbine operating at the same shaft speed, but the pressure ratio where the last-blade-row-choke occurs does recede to a lower value for the variable pitch turbine. This may cause concern of the limit-load achievable by the variable pitch turbine.

For the turbine contingency power production, our calculations show that an amount of 30 to 45 percent extra turbine power, to the nominal take-off power, is obtainable by either of the two methods studied, the throttle push or the steam injection. If the last blade row exit flow is not in over-expansion, the extra power achievable is 35 percent for the throttle push and 30 percent for the steam injection method; when operating at the choked-flow over-expansion, the maximum amount of extra power produced can reach 45 percent by either of the two methods. These results indicate that the tilt-rotor aircraft contingency turbine power requirement of 30 to 40 percent extra to the nominal take-off power can be met by either the throttle push or the steam injection method without resorting to an over-sized engine.

These studies may serve as preliminary views in understanding and in addressing to the challenges presented in the tilt-rotor rotary-wing aircraft engine turbine designs.

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

In this paper, preliminary studies on two turbine engine applications relevant to the tilt-rotor rotary wing aircraft are performed. The first case-study is the application of variable pitch turbine for the turbine performance improvement when operating at a substantially lower shaft speed. The calculations are made on the 75 percent speed and the 50 percent speed of operations. Our results indicate that with the use of the variable pitch turbines, a nominal (3 percent (probable) to 5 percent (hypothetical)) efficiency improvement at the 75 percent speed, and a notable (6 percent (probable) to 12 percent (hypothetical)) efficiency improvement at the 50 percent speed, without sacrificing the turbine power productions, are achievable if the technical difficulty of turning the turbine vanes and blades can be circumvented. The second case-study is the contingency turbine power generation for the tilt-rotor aircraft in the One Engine Inoperative (OEI) scenario. For this study, calculations are performed on two promising methods: throttle push and steam injection. By isolating the power turbine and limiting its air mass flow rate to be no more than the air flow intake of the take-off operation, while increasing the turbine inlet total temperature (simulating the throttle push) or increasing the air-steam mixture flow rate (simulating the steam injection condition), our results show that an amount of 30 to 45 percent extra power, to the nominal take-off power, can be generated by either of the two methods. The methods of approach, the results, and discussions of these studies are presented in this paper.

15. SUBJECT TERMS
Axial flow turbines; Preliminary design and off-design analysis methods; Rotary wing aircraft engines

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