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TRANSITION CONTROL AND PERFORMANCE OF THE SELECTIVE BLEED VARIABLE CYCLE TURBOFAN

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ABSTRACT

The selective bleed turbofan is a two shaft, three compressor, variable cycle aircraft engine. At subsonic flight speeds it operates as a medium bypass turbofan. It becomes a low bypass turbofan when flying faster and is capable of supersonic cruise in the dry mode.

The aim of this paper is to outline the requirements and response of the engine during the transition phase from one mode of operation to the other. Thus it is follow-on work of Ref. 7. To achieve this several control devices can be employed. These are the fuel flow, the variable compressor stators, the nozzle areas and the valve areas of the bypass ducts.

The preliminary analysis described in this paper indicates that all the criteria of performance are satisfied and that the transition can be carried out successfully provided the control variables are co-ordinated properly.

INTRODUCTION

The design of an aircraft engine is a compromise between the various operational requirements of the mission it is expected to fulfill. When engines are required to operate over wide ranges of flight speed and altitudes this compromise becomes progressively more difficult because to be able to achieve all the required mission criteria, the engine designer has to accept certain penalties at each operating point. As the range of operating conditions increases, the penalties become progressively larger. One way of overcoming these difficulties is the variable cycle concept. This requires hardware that will work with radically different thermodynamic cycles at different operating points.

The Selective Bleed Turbofan is such an engine. It is a medium bypass turbofan at subsonic flight conditions. When required, the cycle can be changed to that of a low bypass turbofan at high speeds. In this mode the power plant has a dry supersonic cruise capability. In previous papers its design has been outlined (References 1, 2, 3, 4 and 7) and its benefits and performance have been described in detail.

The current work focuses on the handling characteristics of this engine during the transition period from one mode to the other. Many control variables have to be manipulated in a synchronised manner to ensure that the change of operating mode will take place smoothly and safely.

THE SELECTIVE BLEED ENGINE

The selective bleed engine is a two-spool turbofan (Fig. 1). It has two compressors on the Low Pressure (LP) spool and one compressor on the High Pressure (HP) spool. These compressors are the LP, IP and HP compressors (LPC, IPC, HPC) respectively. Each spool is driven by its turbine, the HP turbine drives the HP compressor and the LP turbine drives the IP and the LP compressor. This configuration proved to be the best after trials with other two spool engines, with two and three compressors.

The engine has been designed to achieve two wide differing missions, good subsonic SFC and a supersonic cruise capability in the dry mode. To achieve these goals it operates in two different manners: the LP mode and the HP mode.

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Low Pressure Mode (LPM) Operation (Fig. 1 a)

- Good dry specific fuel consumption (SFC)
- Bypass from LP compressor exit
- Medium bypass ratio (0.7)
- Medium fan pressure ratio
- Two separate streams

High Pressure Mode (HPM) Operation (Fig. 1 b)

- Cruise dry at Mach 1.40
- Bypass from IP compressor exit
- Medium bypass ratio (0.30)
- High fan pressure ratio
- Mixed exhaust streams

TABLE I. DESIGN POINT PERFORMANCE

MODE	LPM	HPM
ALTITUDE (km)	0	11
Mach NO	0	1.40
TURBINE ENTRY TEMP (TET)(K)	1700	1850
FAN PRESSURE RATIO **	3.7	5.3
COMPR. PRESS. RATIO	5.9	4.9
BYPASS RATIO	0.7	0.30
MASS FLOW (kg/s)	110	74
THRUST (kN)	80	44
SFC AT DESIGN (kg/MNs)	21	37

** the fan comprises the LPC in the LP mode and the LPC and IPC in the HP mode.

Table I illustrates the main cycle characteristics of both the LP and the HP modes. These have been revised since previous publications (Ref. 2,3) to reflect the requirements of a different mission, the engine was originally intended for ASTOVL aircraft applications, while the current paper describes its application to an advanced interceptor. The main change is of a reduced bypass ratio in both modes. It is worth pointing out that in this work, as in all previous work (Ref. 1, 2, 3 and 4) the turbines do not require variable geometry. The engine has an afterburner fitted to it for conditions, such as combat, where a thrust boost is required.

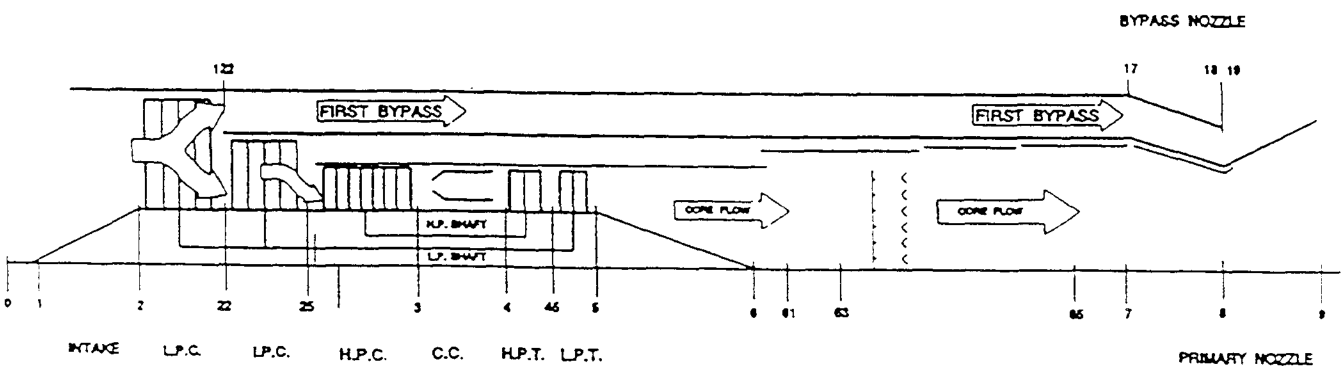
OFF-DESIGN PERFORMANCE

The performance of the engine is shown in the dry mode at an altitude of 11 km in Figures 2 and 3. The parameters shown are those related to the performance (Fig. 2) and operability margins (Fig. 3) of the engine, so the thrust, S.F.C. and compressor operating lines are shown.

The maximum thrust the engine can produce, and how it varies with Mach number, is shown in Fig. 2a. The HP mode thrust is always higher than that of the LP mode. The difference increases with Mach number. This is to be expected because the higher specific thrust of the HP mode reduces the influence of momentum drag.

Fig. 2b shows the S.F.C. of both modes. it can be seen that the S.F.C of the HP mode is always higher. At low speeds it is 20 percent higher, while at high speeds it is only 10 percent higher. It must be pointed out that the high Mach Numbers shown for the LP Mode are for completeness. At those speeds the engine will not be able to produce the thrust required by the aircraft unless it is operating in the HP mode.

Fig. 1a Engine Stations - Low Pressure Mode



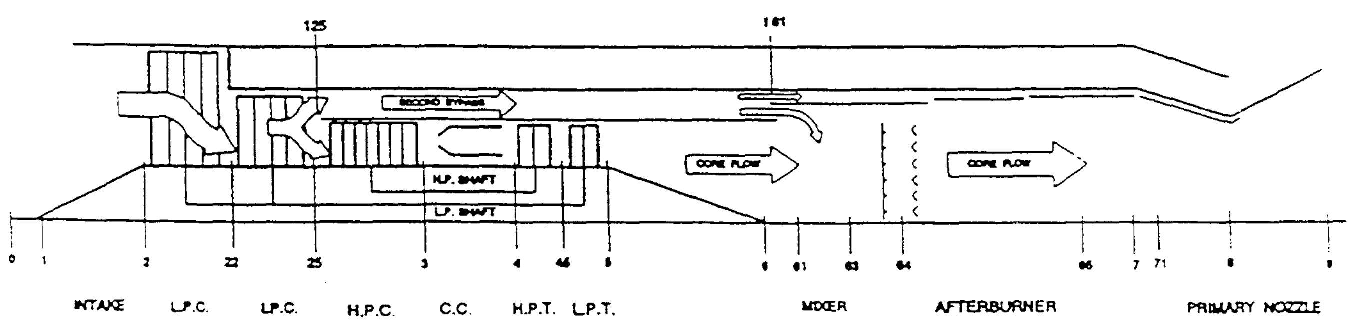


Fig. 1b Engine Stations - High Pressure Mode

Figure 3a and 3b show the operating lines on the LP and IP Compressors, respectively, and the effect of turning the stators on the characteristics. In both cases the surge margin is adequate. An examination of these figures shows the large change in non-dimensional mass flow required during the transition phase. Figure 3c shows the trajectories of the HP Compressor. No major difficulty is foreseen in the case of this component because the HP Turbine is operating between choked nozzles.

HANDLING AND CONTROL VARIABLES

The engine design point is at an altitude of 11 km, flight Mach number of 1.40, in the HP mode. Once the preliminary design calculations were carried out, engine performance throughout the flight envelope was obtained. For this purpose an engine specific computer program was written (Ref. 6), employing the main principles of TURBOMATCH, the Cranfield Gas Turbine simulation system (Ref. 5).

The aim of the analysis was to establish the ability of the engine to change from one mode to the other safely and smoothly. To achieve this several parameters can be manipulated to enable satisfactory engine handling. These are:

- Fuel flow
- LP and IP compressor variable stators
- Nozzle area
- Valve settings

These variables have to be manipulated in such a way that the engine will function safely throughout the transition period. The level of TET should be within the safety boundaries of the steady state operation of the engine, Surge margins should be adequate, component efficiencies must be high. In addition thrust levels have to be maintained at a satisfactory level during this transient. If at all possible, to ensure a fast transient response, shaft speed changes should be small.

CONTROL VARIABLE MANIPULATION

There are two valves in the engine, one controlling the flow from the LPC delivery and the other from the IPC delivery. As one opens, the other one closes. These movements take place simultaneously.

To clarify the description of the transition, the process has been quantified using the Low Pressure Valve opening as a frame of reference. So, in this paper, when the process of transition is 80 percent complete this means that the change from HP mode to LP mode is 80 percent complete, therefore the LP delivery valve (LPV) is 80 percent open while the IP delivery valve (IPV) is 20 percent open.

It was found that the transition could be carried out in a reasonable way by manipulating the fuel flow so that the TET varies linearly with the valve area. Also, during the transition phase nozzle area change was not required. Table II shows the variation of some of the control parameters during the transition period.

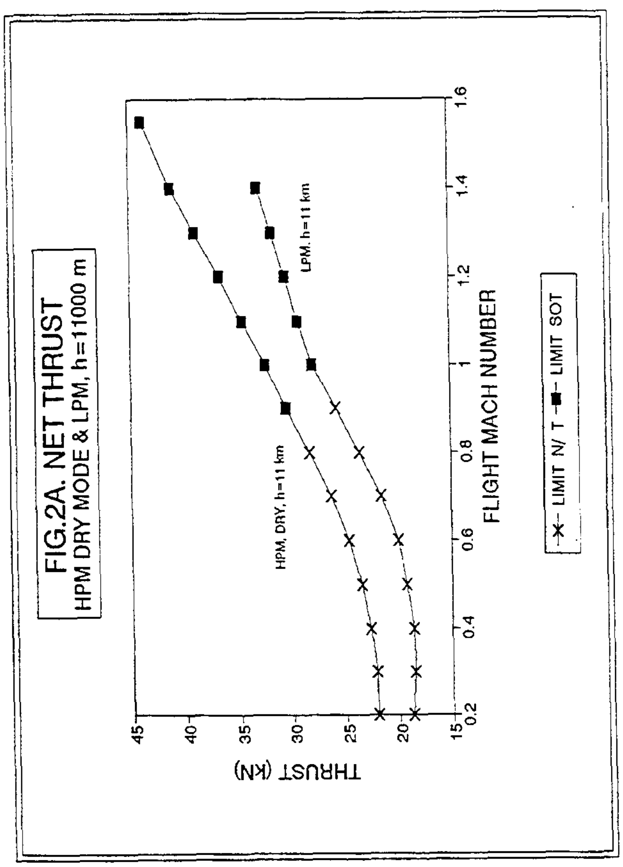


FIG.2A. NET THRUST
HPM DRY MODE & LPM, h=11000 m

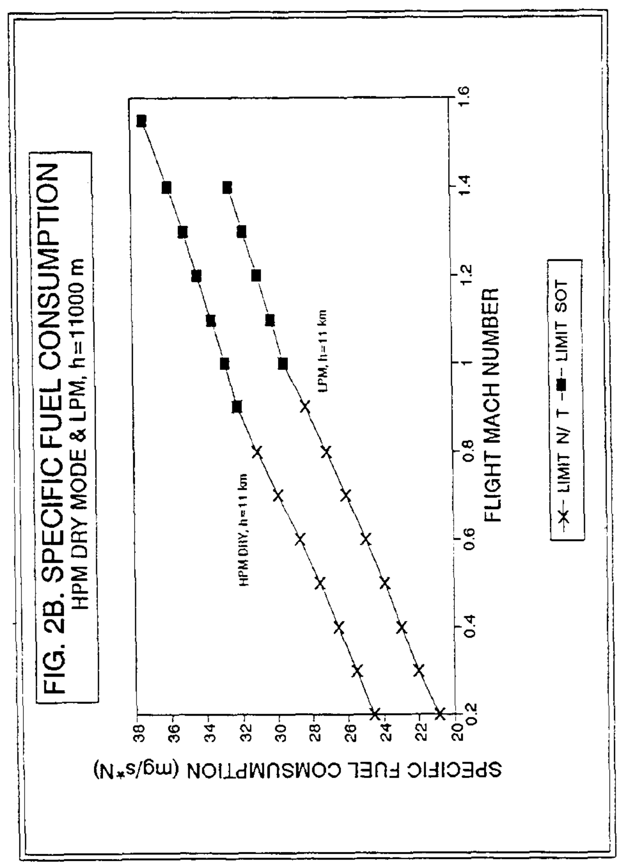


FIG. 2B. SPECIFIC FUEL CONSUMPTION
HPM DRY MODE & LPM, h=11000 m

TABLE II. TRANSITION PHASE

	Phase	IPV	LPV	TET
HPM	0.0	1.0	0.0	1850
	0.1	0.9	0.1	1835
	0.2	0.8	0.2	1820
	0.3	0.7	0.3	1805
	0.4	0.6	0.4	1790
	0.5	0.5	0.5	1775
	0.6	0.4	0.6	1760
	0.7	0.3	0.7	1745
	0.8	0.2	0.8	1730
	0.9	0.1	0.9	1715
LPM	1.0	0.0	1.0	1700

The other control parameter that is manipulated during the transition is the angle of the LPC and IPC stators. Several variable stator schedules are possible, two were tried, one where the stators vary linearly with the change in valve setting and the other where the vary with a parabolic law.

Figure 4 shows these laws, it can be observed that the IPC stators turn more than those of the LPC. It was found that the best of these two schedules was the one that obeys the parabolic law because it gives better LPC surge margin and higher IPC efficiencies. This one will be the main focus of this paper. It is assumed, at this stage, that the transition is a slow process; therefore the analysis described in this paper is a quasi-steady state one. A future development will be the examination of fast transitions and their dynamic implications. The analysis described in this paper has been performed for simulated I.S.A.S.L.S. conditions. In practice any other point could have been chosen.

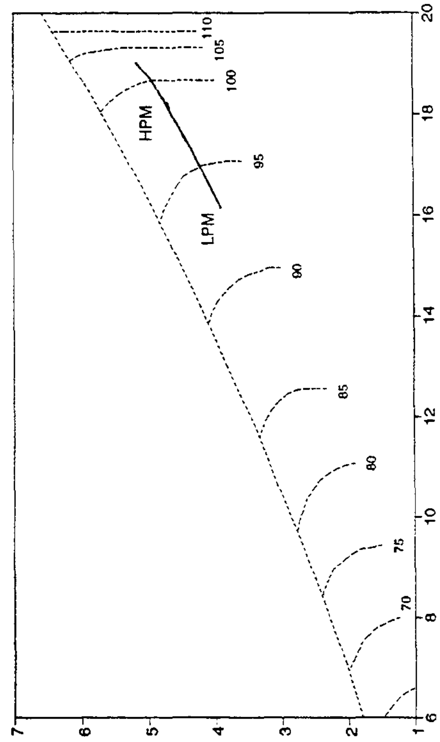


FIG.3C. OPERATING LINE IN THE HPC
HPM DRY MODE & LPM, h=11000 m.

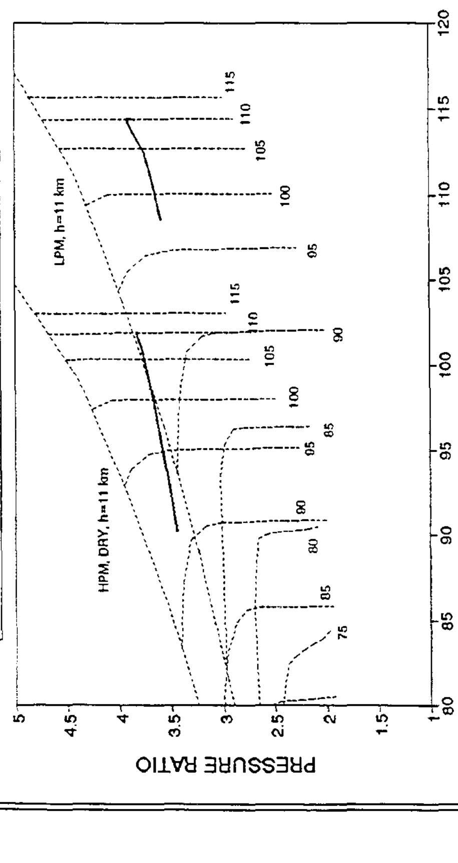


FIG. 3A. OPERATING LINE IN THE LPC
HPM DRY MODE & LPM, h=11000 m

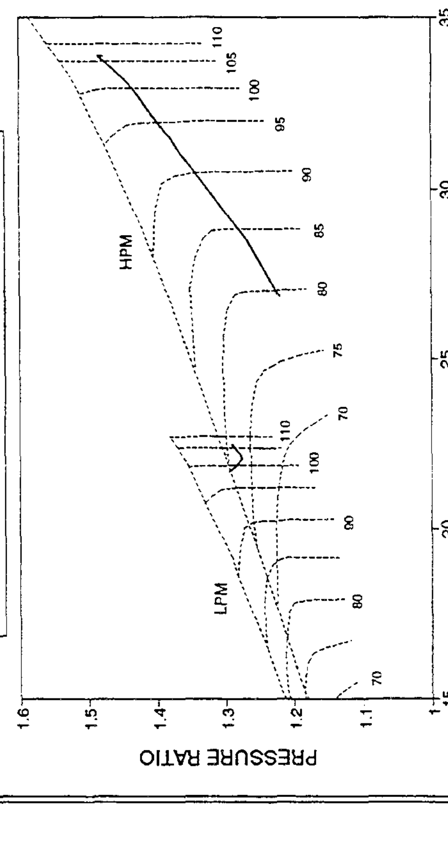


FIG 3B. OPERATING LINE IN THE IPC
HPM DRY MODE & LPM, h=11000 m

PERFORMANCE DURING THE TRANSITION

In this section the performance of the engine is described during the transition period. The focus is on performance and safety issues. Therefore the parameters shown in Figure 5 are the operating lines, thrust, bypass ratio, compressor efficiencies and shaft speeds.

Compressor operating lines

Fig. 5 shows the paths on the compressor characteristics. In the case of the LPC and IPC two sets of characteristics are shown, those of the HP and those of the LPMode. It can be seen clearly how the LP compressor moves to a region of higher mass flow, as required by the increased bypass ratio. While the IP compressor moves to a region of lower mass flow, ie diverting more flow to the bypass duct. The HPC trajectories (Fig. 5c) do not exhibit anything special, as would be expected from a compressor whose turbine is operating between choked nozzles.

Thrust

During the transition phase from HP mode to LP mode, the thrust will fall by about 15 kN. This change is shown in Fig. 6a, where the core, bypass and total thrust levels are shown as the change of mode progresses. In the HP mode the core thrust includes the bypass thrust because the two flows are mixed prior to them being discharged through the core nozzle. In the LP mode the two flows discharge through separate nozzles.
In Fig. 6a it can be observed there is a large reduction in the core thrust as the operating point approaches the LP mode. This is only partly compensated by the increase in bypass thrust, so the overall thrust of the engine is reduced.

Bypass ratio

The philosophy of the Selective Bleed Engine is to allow a large modulation of bypass ratio. This change is shown in detail in Fig 6b. the IP bypass ratio gradually falls as the LP bypass ratio rises. It can be observed that the change in bypass ratio is not linear with change in valve setting. This is because of the influence of the variable compressor stators which are following a parabollic law.

Compressor efficiencies

The change of variable stator angles of the compressors is going to have an effect on the efficiencies because the operating point on the characteristics is changed. Fig. 6c shows these changes. The IPC is the compressor that undergoes the largest changes in efficiency. It can be observed that there is a very large reduction in efficiency until the change of mode is two thirds complete. Then the efficiency recovers slightly but in the LP mode is well below that of the HP mode. The reason for the large change in IPC efficiency when compared to those of the other two compressors is the very large movement of the IPC stator angles.
During the transition, the LPC exhibits a relatively small change in efficiency, while the HPC efficiency remains nearly constant.

Shaft rotational speeds

It was anticipated that during the change of mode the rotational speeds of the two shafts, and their ratio, will change. This can be observed in Fig. 6d.
The HP shaft speed falls by about 4 percent because of the lower operating point demanded from this compressor in the LP mode. The LP shaft on the other hand exhibits a small reduction in speed until the change of mode is one third complete. Beyond that, the speed starts to rise until the process is 80 percent complete, after which point it starts to fall again. When the transition is complete the LP shaft speed is just under 1 percent higher than it was in the HP mode.
The speed changes are relatively small during the transition. This is important because it means that these transients can be completed relatively quickly. The largest resistance to a change of state of an engine is provided by the inertia of the rotors, the larger the change of rotational speed they have to experience, the larger the time interval required to achieve that change. The magnitude of the shaft speed changes exhibited by the Selective Bleed Engine is a sign that its transient response is fast.
The speed excursions predicted for the LP shaft can be reduced by further refining and tuning the valve, variable stator and fuel schedules. Further work will be carried out in this fine tuning because there is a strong incentive to reduce the speed excusrions of the LP shaft speed. If a constant speed transient can be acheved for this shaft the transition will be much faster.

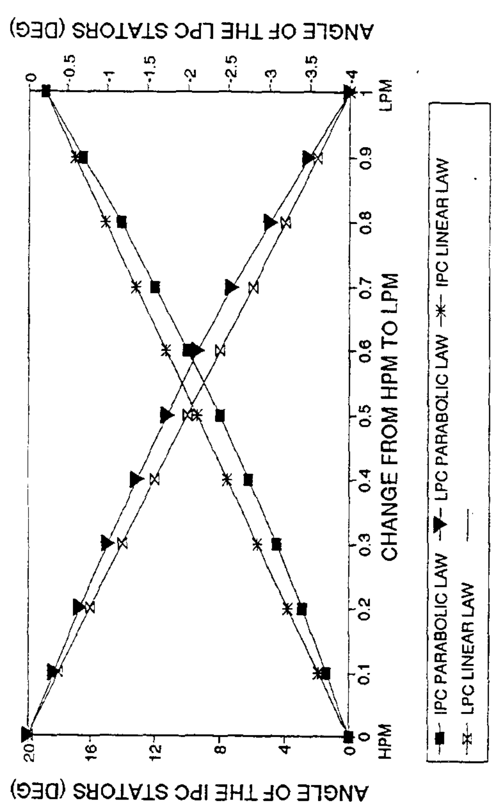


FIG.4. VARIATION OF STATOR ANGLES
LINEAR AND PARABOLIC LAWS

CONCLUSION

The analysis of the transition, from one mode to the other, of a variable cycle engine has been carried out. The main conclusion to be drawn from this work is that there appear to be no major problems during the transition phase. All components appear to be operating in regions of safe and satisfactory performance. Perhaps the one element that may cause concern is the large drop in efficiency of the IP compressor. Large reductions in efficiency are not acceptable because they may negate the benefits to be accrued by operating the engine with a better thermodynamic cycle.

There are some questions of detail still to be analysed, such as the correct choice, synchronisation and implementation of the control schedules. These are the fuel flow, variable stator setting of two compressors and the scheduling of the two valve areas.

The large changes in efficiency of the IP compressor suggest that its aerofoils should be designed more lightly loaded to allow it to operate with a better efficiency over a wider range of operating conditions.

The Shaft speed changes observed were small. This result is very encouraging bacause it is an indication that the transient response during the change of mode can take place rapidly.

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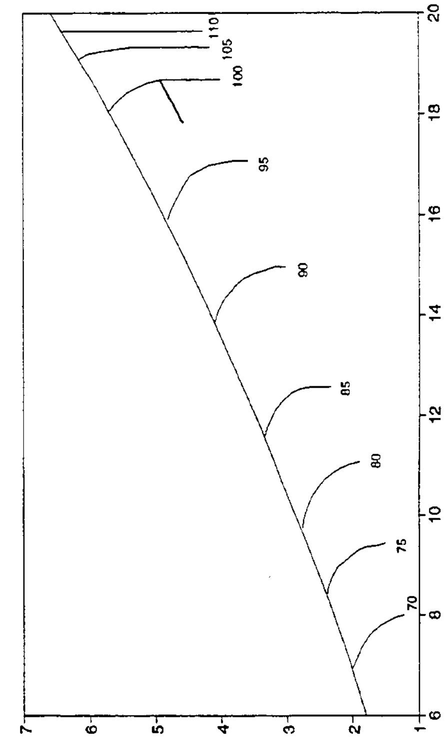

FIG.5C. HP COMPRESSOR
CHANGE BETWEEN HPM AND LPM, M=0 h=0 m

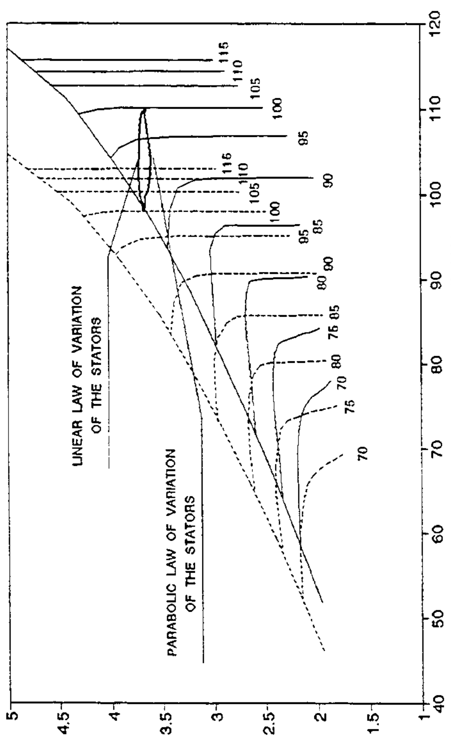

FIG.5A. LP COMPRESSOR
CHANGE BETWEEN HPM AND LPM, M=0 h=0 m

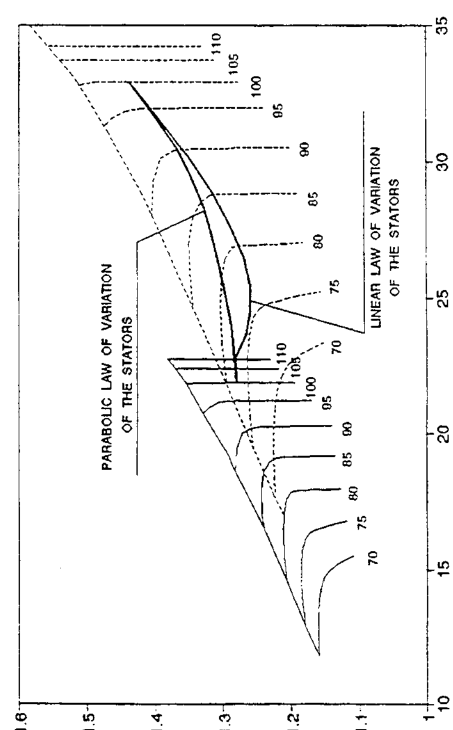

FIG.5B. IP COMPRESSOR
CHANGE BETWEEN HPM AND LPM, M=0 h=0

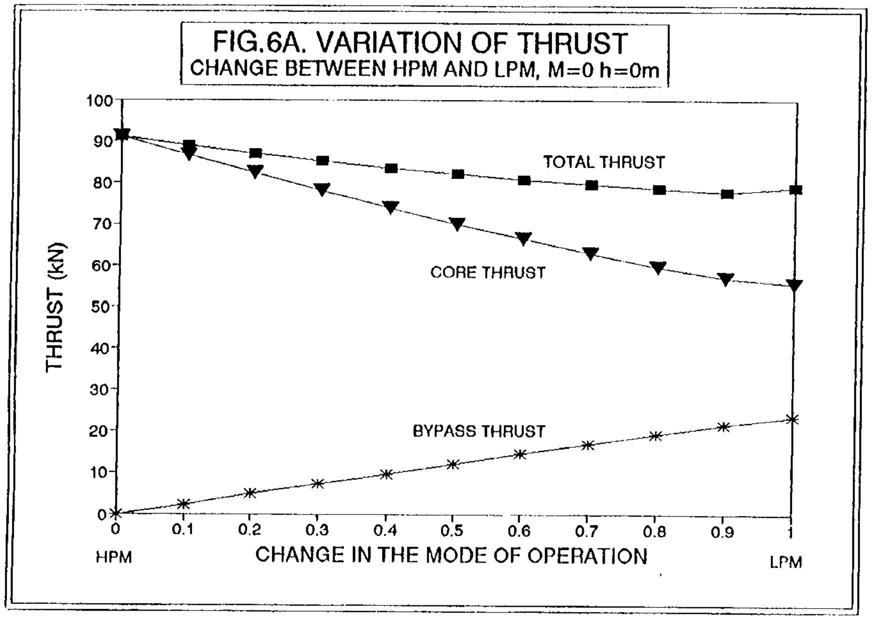

FIG.6A. VARIATION OF THRUST
CHANGE BETWEEN HPM AND LPM, M=0 h=0m

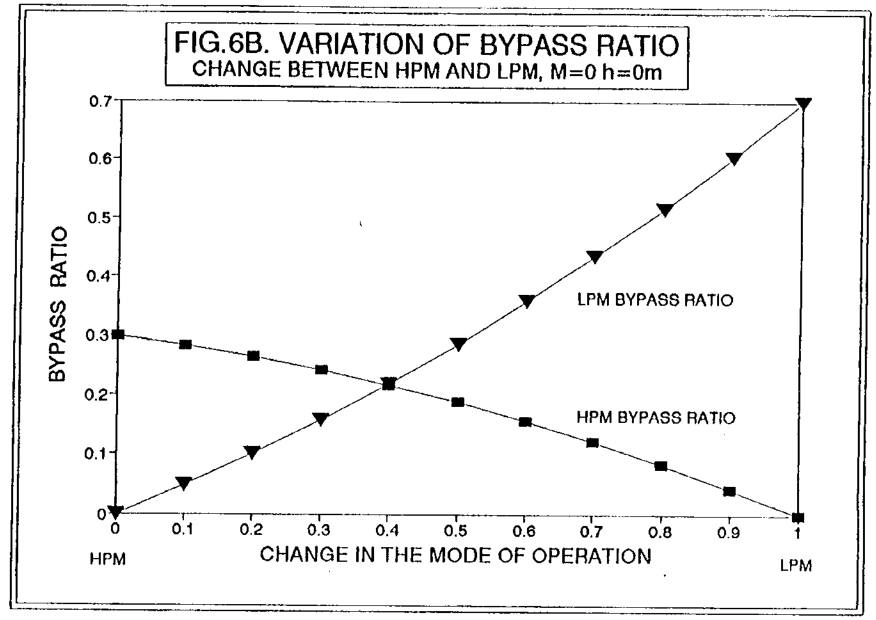

FIG.6B. VARIATION OF BYPASS RATIO
CHANGE BETWEEN HPM AND LPM, M=0 h=0m

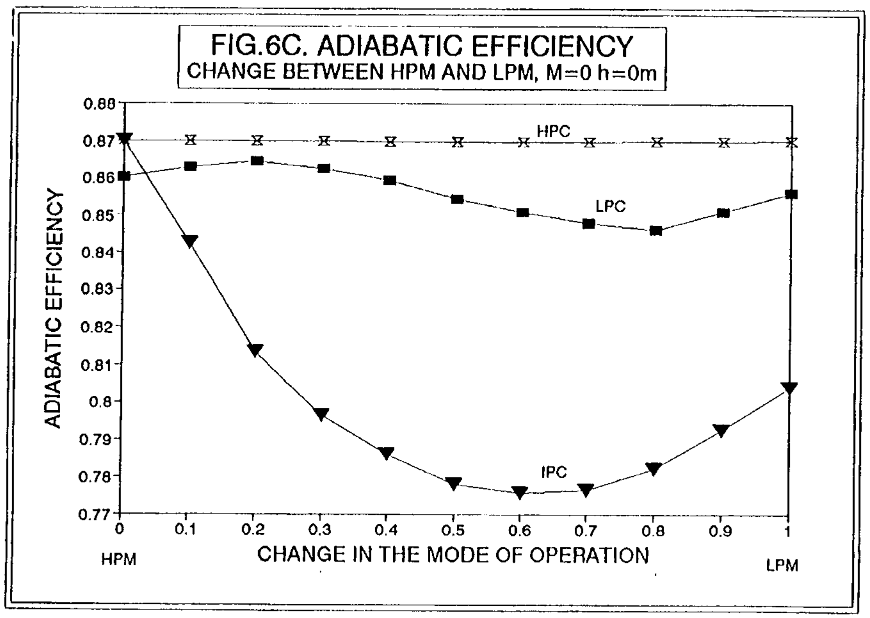

FIG.6C. ADIABATIC EFFICIENCY
CHANGE BETWEEN HPM AND LPM, M=0 h=0m

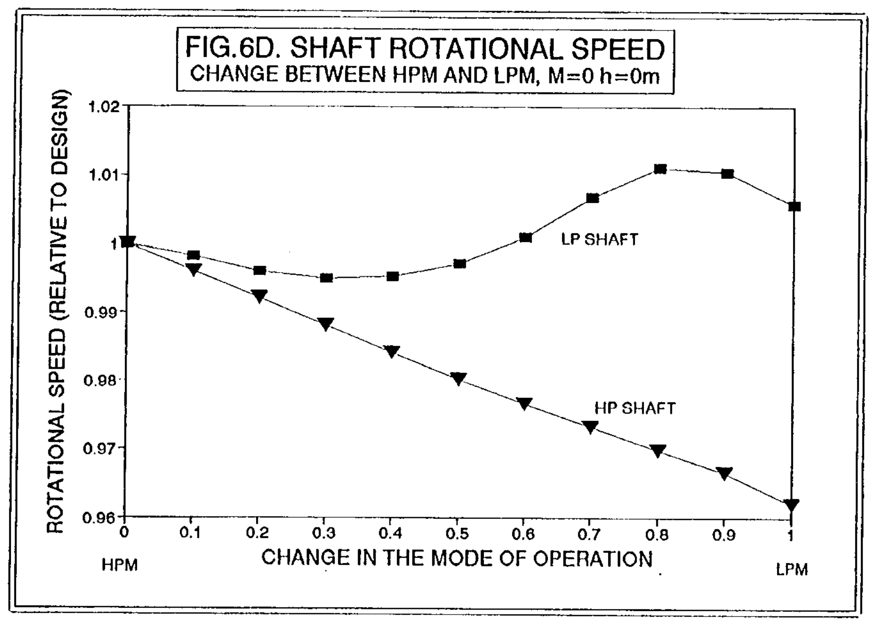

FIG.6D. SHAFT ROTATIONAL SPEED
CHANGE BETWEEN HPM AND LPM, M=0 h=0m

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