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FROM SINGLE ROTATING PROPFAN TO COUNTER ROTATING DUCTED PROPFAN PROPELLER/FAN CHARACTERISTICS

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Abstract

Within this paper the relationship between a propeller, a propfan and a fan as propulsors will be worked out. The advance ratio, thrust- and power coefficient for different blade settings can be converted into the frame of a fan performance map i.e. pressure ratio against mass flow. For a fixed flight Mach number all possible operating points, that is rotating speed, blade angle setting, pressure ratio and mass flow, coincide with one characteristic throttle line, the basis of which can be deduced from one-dimensional gasdynamic considerations. To show this in more detail the performance behaviour of various propfan concepts-unshrouded and shrouded-have been simulated by a computer program on a one-dimensional, compressible basis. From this an operating line versus flight Mach number may be found corresponding to an optimal blade angle setting of the first and second rotor.

Nomenclature

Symbols:

A	flow area
c	absolute flow velocity
c_p	specific heat (p const)
C_P	power coefficient
C_T	thrust coefficient
D_{ref}	tip diameter
F_T	thrust
H	flight height
h_t	total enthalpy
i	flow incidence angle
J	advance ratio
M	Mach number
$\dot{m}$	mass flow
n	rotor speed
P	shaft power
$p (p_t)$	static (total) pressure
$T (T_t)$	static (total) temperature
u	rotational velocity
$\Delta\beta$	blade setting angle
η_{net}	net-efficiency (thrust power/shaft power)
η_{is}	isentropic efficiency
κ	ratio of specific heats
π	total pressure ratio
ρ	density
ω	cascade loss coefficient

Subscripts:

0	plane far upstream
1	inlet plane (1. Rotor)
2	outlet plane (2. Rotor)
3	plane far downstream
ax	axial direction
max	maximum value
min	minimum value
u	rotational direction

Abbreviations:

DCR	Ducted Rotating
DP	Design Point
UCR	Unducted Counter Rotating
USR	Unducted Single Rotating

1. Introduction

In aviation propulsion always is jet propulsion, no question wether a propeller - ducted or unducted - or a modern high bypass jet engine is applied. The thrust achieved by accellerating a quantity of incoming air flow above flight velocity has a common basis in the momentum equation.

By developing the propfan concept in the seventies i.e. higher loaded propellers for high subsonic flight velocities the importance of the classical definition of propulsive efficiency was picked up again melting the ultra high bypass propeller concept with the today's bypass fan engines.

In general a fan engine man's point of view is directed towards compressor mass flow, pressure ratio and isentropic efficiency, whereas a propeller man is looking for power coefficient, advance ratio and net efficiency. Since a fan compressor of a high bypass fan engine or a propeller can be considered as pressure rising devices anyway, a common fundamental basis may be found for both combining compressor and propeller terminology. It is for practical and experimental reasons to prefer the one or the other notation. For an analytical approach the fan compressor terminology will hold for both the concepts, which will be shown in this paper.

2. A General Propulsion Concept

A propeller or fan-compressor as shown in Fig.1 is acting in its given surrounding so that the characteristic operating lines of a propulsor can be deduced by applying the one-dimensional gasdynamic fundamental equations (continuity, energy and momentum). That is the corrected mass flow as a function of flight Mach number, pressure ratio, isentropic efficiency, inlet recovery, nozzle losses and nozzle area (plane 3). The corrected mass flow refered to the inlet plane (1) is given by

$$\dot{m}_{cor} = \dot{m}\,\frac{\sqrt{T_{t1}/T_{ref}}}{p_{t1}/p_{ref}} \tag{1}$$

with T_{ref}=288.15K p_{ref}=101325Pa
The general correlation will then be:

$$\frac{\dot{m}_{cor}}{A_3} = \frac{p_{ref}}{T_{ref}}\,\frac{\pi}{\sqrt{\frac{T_{t2}}{T_{t1}}}}\left(\frac{p_2}{p_{t2}}\right)^{\frac{1}{\kappa}}\sqrt{\frac{2\kappa}{R(\kappa-1)}\left[1-\left(\frac{p_2}{p_{t2}}\right)^{\frac{\kappa-1}{\kappa}}\right]} \tag{2}$$

with

$$\frac{p_2}{p_{t2}} = \frac{1}{\left(1+\frac{\kappa-1}{2}M_0^2\right)\pi}$$ without inlet and nozzle pressure losses

$$\frac{T_{t2}}{T_{t1}} = 1 + \frac{\pi^{\frac{\kappa-1}{\kappa}}-1}{\eta_{is}}$$ $R = 287\ \frac{J}{kg\ K}$ gas-constant

In general Equ.2 is valid for propellers or ducted fans if the area of plane 3 is known. Normally, for ducted fans this area is the nozzle area, whereas for unducted propellers/propfans this area is a variable at infinity. In order to have a geometrically fixed area for the unducted concept it is convenient to take the rotor inlet plane as the reference area.

By using Froude's theorem of an average axial velocity between plane 0 and plane 3 to be the inlet value (plane 1) the equivalent to equ.2 then is:

$$\frac{\dot{m}_{cor}}{A_1} = \frac{1}{4}\,\frac{p_{ref}}{\sqrt{T_{ref}}}\sqrt{\frac{\kappa}{R}}\left(\frac{1}{1+\frac{\kappa-1}{2}M_0^2}\right)^{\frac{\kappa+1}{2(\kappa-1)}}\cdot \left(M_0 + M_2\sqrt{\frac{\pi^{\frac{\kappa-1}{\kappa\eta_{pol}}}}{\pi^{\frac{\kappa-1}{\kappa}}}}\right)\cdot\left(1+\frac{\pi^{\frac{\kappa-1}{\kappa}}}{\pi^{\frac{\kappa-1}{\kappa\eta_{pol}}}}\right) \tag{3}$$

with $$M_2 = \sqrt{\frac{2}{\kappa-1}\left[\left(1+\frac{\kappa-1}{2}M_0^2\right)\pi^{\frac{\kappa-1}{\kappa}}-1\right]}$$

The polytropic efficiency is used for simplification, since for low pressure ratios only a small difference to the isentropic efficiency exists.

The results of equations 2 and 3 are shown in Fig.2 and Fig.3 respectively. These are the operating lines the ducted fan or the unducted propeller/propfan have to meet either at design or off-design operating. To illustrate this in more detail a computer program has been established to simulate any operating point of a propulsion concept in an arbitary surrounding either in a wind tunnel or in actual flight.

Three different concepts will be considered (Fig.4):

1) the <u>unducted single rotating propfan</u> (USR) like the NASA SR3 propfan developed by Hamilton Standard (Ref.1).
2) the <u>unducted counter rotating propfan</u> (UCR) similar to the unducted fan of General Electric.
3) the <u>ducted counter rotating propfan</u> (DCR) similar to the concept developed by MTU.

As the comparison of these concepts is based on a computer simulation only the NASA SR3 propfan has been selected as the basic concept because for this concept experimental data for design and off-design (Ref.1) are available. The following design data are kept constant for all three concepts:

flight altitude	H	= 10668m
flight Mach number	M_0	= 0.8
cruise thrust	F_T	= 20kN
maximum tip speed	u_{max}	= 244 m/s
inlet hub-to-tip ratio		0.25
power split (Rotor1:Rotor2)		1:1

The pressure ratio of concept 1 (~1.06) is a result of design point matching, whereas the pressure ratio of concept 2 is a free choice of 1.13 and of concept 3 was chosen around 1.24 to have a just unshoked nozzle at flight Mach number 0.8.

A survey on the geometrical size of these concepts is given in Fig.5. The calculated diameters are primarily be influenced by the choice of the pressure ratio.

3. A Propulsion Simulation Tool

Two computer programs have been developed on a simple one-dimensional but compressible basis to evaluate off-design operation of either unducted or ducted propulsors under wind tunnel test or flight conditions. The basic principle of these programs is to start with a design point calculation which is used as an input of the succeeding off-design calculation as shown in Fig.6. The fan herein can be represented by the choice of an adequate blade height at inlet, the radius of which then is hold constant throughout the machine (plane 1 to 2). Euler's momentum equation delivers the velocity triangles which are used also for off-design, i.e. the relative outlet flow angles of the blades are hold constant. Thus, any lower inlet velocity leads to a higher pressure ratio by higher turning angles and vice versa.

$$\Delta h_t = u\,(c_{u\ Rotor\ out} - c_{u\ Rotor\ in}) = c_p T_{t1}\left(\pi^{\frac{\kappa-1}{\kappa}}-1\right)/\eta_{is} \tag{4}$$

Pressure ratio and mass flow are adapted iteratively to the requirements of the outer flow field, i.e. the static pressure at outlet plane 3.

Since the unducted fan does apriori not have a defined outlet area at plane 3, the theorem of Froude for a jet flow

$$c_1 = 0.5 \quad (c_o + c_{3ax}) \tag{5}$$

has been applied for matching the inlet velocity with the flow expansion between plane 2 and 3 to cope with the static pressure. For a single rotating fan the aftswirl velocity is kept constant, with the swirl angle slightly changing by accellerating via the flow. For design and off-design the axial velocity component throughout the fan is assumed constant resulting in an variable area ratio (plane 2/plane 1) at off-design which is contrary to the ducted concept.

For the ducted concept the duct geometry i.e. the area ratios from the inlet to the nozzle must be known. It can either be prescribed or - as done here - calculated with the assumption that the axial flow velocity component is constant over the fan at design. Additionally, the fan inlet Mach number at design must be prescribed to fix the fan design velocity triangles. Here it is arbitrarely set to the cruise flight number (M_1= 0.8) knowing that choking may occur due to hub blockage. The physical blade shape is not included into the program. The blades are just represented by their flow turning characteristics.

Originally, the program was run with a constant isentropic efficiency, but more realistic data required prescription of blade loss characteristics equivalent to compressor cascade loss coefficients.

Fig.7 illustrates a typical cascade loss curve versus incidence angle i (i=0 =design point). The basic function was assumed to be a square function of incidence. Any other type of curve may be used. The loss coefficient is defined by

$$\omega = \frac{p^{+}_{t\,Rotor\,in} - p^{+}_{t\,Rotor\,out}}{p^{+}_{t\,Rotor\,in} - p_{Rotor\,in}} \tag{6}$$

wherein the total pressures are depicted from the rotor relative system ($^+$).

The program varies iteratively the isentropic efficiency to meet the prescribed loss coefficients. Additionally, a prescribed turning deviation of the blades can be introduced to approach the reality more adequately, but is not done within this investigation.

So far, the unducted and ducted propfan are treated as a compressor anyhow. Since all values as pressure ratio, mass flow, efficiency, thrust and rotor speed are calculated the propeller or the compressor characteristic are identified as desired. The definitons of the propeller characteristic herein are:

Advance ratio $J=c_o/(n\, D_{ref})$

Power coefficient $C_P=P/(\rho_o n^3 D_{ref}^5)$

Thrust coefficient $C_T=F_T/(\rho_o n^2 D_{ref}^4)$

Net efficiency $\eta_{net}=F_T\, c_o/P$

Power loading P/D_{ref}

D_{ref} is the outer diameter of the first rotor, and no change is anticipated during different blade angle settings.

The inlet corrected rotor speed is given by

$$n_{cor}=n/\sqrt{T_{t1}/T_{ref}} \tag{7}$$

As the calculation of average values is done one-dimensionally for a constant radius the choice of this radius, i.e. the position of the blade height taken as the representative one, is governing the average output of pressure ratio, isentropic efficiency and loss coefficient at design and off-design.

This is demonstrated in Figs.8 and 9 for the NASA SR3 single rotating propfan which is chosen as the reference. In order to reproduce design point values of C_p=1.69 and η_{net}=78.8% different isentropic efficiencies and pressure ratios depending on the chosen position of blade height have to be taken as an input (Fig.8) representing the actual average. This of course is due to the resulting velocity triangle combined with the residual swirl. At off-design (Fig.9) the choice of the radial position effects the gradient of the power coefficient versus advance ratio and the resulting efficiencies. So the radial position is the key parameter to match off-design values with the realistic gradients given for instance by experiments. Although the NASA SR3 propfan is best represented at a blade height of about 43 percent, for the comparison of all three concepts a blade height of 50% was chosen as the representative one.

4. Calculated Propfan Characteristics

The first step of the simulation is to fix the design points of all three concepts to compare. These data are given in Table 1. For the data of the ducted concept another set of data at a lower inlet Mach number is included just for comparison. The design values to hold are specially marked, all other values being calculated results. For the counter-rotating concepts the isentropic efficiency increases with pressure ratio because the blade cascade losses are kept within certain limits not too far away from the data of the basic USR concept. Since a loss of 1.4% could not be realized for both the rotors, the limit was set to 1.6% for the first and to 1.4% for the second rotor. The net-efficiency is substantially higher compared to the single rotating version due to zero swirl at the outlet.

The next step of the simulation is running the program in the wind tunnel mode, that is flight conditions at reference pressure and temperature (zero flight height), and varying flight Mach number, corrected rotor speed and blade angle setting (simultaneously for each rotor).

After this, the auto blade setting is activated for 100% corrected rotor speed to give the optimal blade setting for various flight Mach numbers, i.e. zero incidence at each rotor inlet.

Fig.10 and Fig.11 submit the analytical results of the single rotating propfan concept. Fig.10 illustrates the propeller characteristics at constant flight Mach number and different blade angle settings. Rotor speed variation is implied by changing the advance ratio J at constant flight speed. The results of the same concept in fan-compressor terminology i.e. pressure ratio versus corrected mass flow for different corrected constant speed lines and different blade setting for the 100% speed.

The unducted propfan is "throttled" by the different flight Mach numbers as it was expected from Fig.3 (Chapter 2). For any rotor speed and blade angle setting the operating points are fixed by the actual flight Mach number. Starting with the design point the operating points for optimal blade angle setting (zero incidence) at 100% corrected speed can be deduced showing a slight decrease in pressure ratio, a tendency found in general for all concepts.

Similar characteristics are found for the unducted counter rotating concept (Figs.12 and 13), but at a higher level of pressure ratio. In Fig.13 the isentropic and net-efficiencies are presented, showing that the optimal blade angle setting meets the maximum compressor isentropic efficiencies, but the corresponding net-efficiencies are below maximum. To reach a higher net-efficiency at any blade setting means decreasing the pressure ratio by increasing flight Mach number and mass flow. This will then give a higher propulsive efficiency exeeding the loss in isentropic efficiency. But the disadvantage is a substantial loss in thrust (compare Fig.14).

As the last example the performance characteristics of the ducted counter rotating propfan are presented in Figs.15 and 16. Although a propeller characteristic is optained (Fig.15), main emphasis is now put upon the fan-compressor performance terminology. Fig.16 shows good qualititative agreement of the data with the operating lines expected from Fig.2. There is obviously no fundamental difference in the perfromance behaviour of a ducted fan-compressor concept compared with the previously analyzed unducted concepts, because the method applied has the same common basis. The strong decrease of net-efficiency at optimal blade setting for lower mass flow equivalent to lower flight Mach number again is the hidden influence of the dominating propulsive efficiency due to a higher level of pressure ratio (Ref.2). Realizing values of higher net-efficiencies in this configuration at off-design again means decreasing the pressure ratio and by this loosing thrust. For a constant off-design blade setting the pressure ratio can only be decreased by either increasing flight Mach number at constant corrected rotor speed or decreasing rotor speed at constant flight Mach number. Anyway the level of thrust has to be matched with the demand of an aircraft's flight mission in reality.

Due to the necessarily large mass flow variation of all three analyzed concepts variable pitch rotor blades must be used to cover the whole flow regime from takeoff to cruise. Fig.17 focuses on the optimal blade angle settings. The highest variation - as expected from Figs.1 or 2 - has to be applied for the unducted concepts due to their low pressure ratios.

In the unducted counter rotating case the blades of both the rotors may be set equally whereas in the ducted counter rotating concept a tendency for desynchronized blade setting is revealed. It must be emphazised that the rotor speeds herein are synchronized and that the design power split for the two rotors was set equal. Using a planetary differential gear a deterioration in power split according to the gear has to be taken into account.

Conclusion

For three actual concepts of today's propfans - unducted single rotating, unducted counter rotating and ducted counter rotating - a common basis of preliminary performance assessment has been developed.

A compressible, one-dimensional simulation program was found to have a good potential for predicting roughly the flight characteristics of the various concepts in terms of propeller or fan-compressor terminology. The aim was to keep the program as simple as possible, to maintain a flexible adaption to any test conditions, a wind tunnel or a flight szenario. By this a compromise between mere overall thermodynamics and mere flow aerodynamics within a fan itself could be achieved. A simple coupling of both is a first important step to understand what a concept actually is to perform at design and particularly at off-design.

References

(1) Rohrbach, Metzger, Black, Ladden — Evaluation of Wind Tunnel Performance of an Advanced 45° Swept Eight Bladed Propeller at Mach Numbers from 0.45 to 0.85. NASA Contract Report 3505, 1982.

(2) Schimming — Vergleichende Kreisprzeß-rechnungen für ein Prop-fan/Turbofan Triebwerk. DFVLR Mitteilung 82-18.

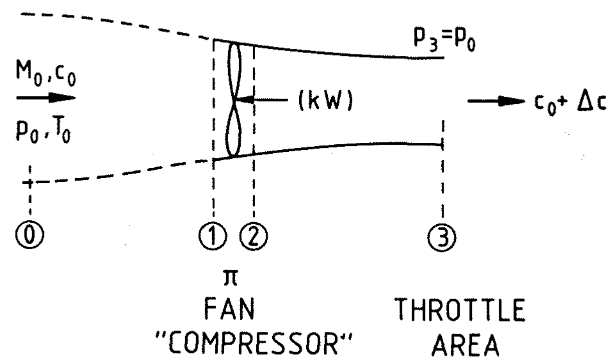
Concept → / Quantity ↓		USR (SR3 NASA)	UCR	DCR	DCR*
Pressure Ratio		1.0578	◤ 1.130	◤ 1.240	◤ 1.240
Isentropic Efficiency	%	89.5	89.3	93.8	94.5
Loss Coefficient	Rotor 1	0.0142	◤ 0.0151	◤ 0.0158	◤ 0.0159
	Rotor 2		0.0139	0.0135	0.0132
Inlet Diameter	m	4.500	2.900	2.255	2.313
Hub-to-Tip Ratio		◤ 0.25	◤ 0.25	◤ 0.25	◤ 0.25
Mass flow	kg/s	1357	568	337	336
Speed	1/min	1036	1471	2066	2015
Inlet Mach number		0.829	0.868	◤ 0.80	◤ 0.70
Thrust	N	◤ 20189	◤ 20048	◤ 20068	◤ 20007
Power	kW	6080	5621	5647	5594
Power Loading	kW/m^2	◤ 300	668	1110	1046
Net Efficiency	%	◤ 78.8	84.6	84.3	84.8

* Design Point only for comparison

◤ Prescribed value to achieve

TABLE 1

Calculated concept design point values modelled for a 50% blade height position
$H=10668m$ $M_o=0.8$ $u_{max}=244$ m/s



$\frac{\dot{m}_{cor}}{A_3} = f(M_0, \pi, \eta_{is})$	$\dot{m}_{cor} = \dot{m}\,\frac{\sqrt{T_{t_0}/T_{Ref}}}{p_{t_0}/p_{Ref}}$

Fig.1 Basic concept of propulsion

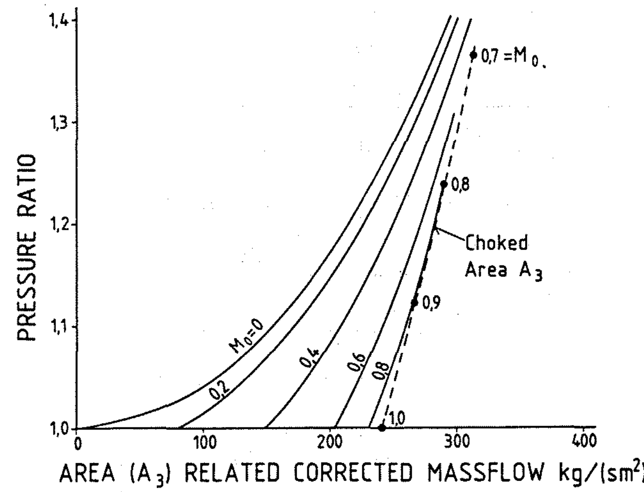


Fig.2 General operating lines by different flight Mach numbers. Equation (2) $\eta_{is} \sim 0.92$

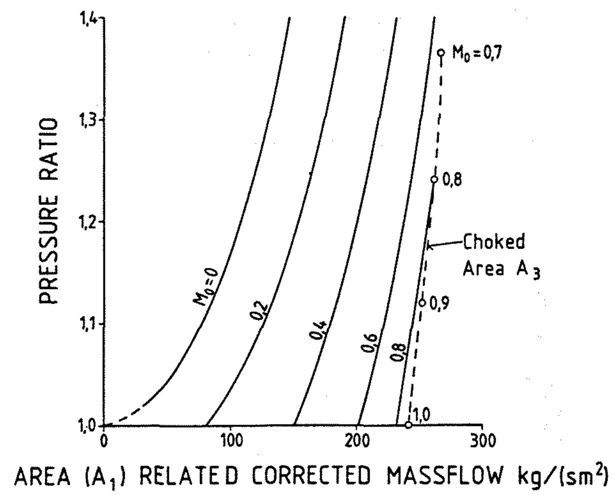


Fig.3 Operating lines for different flight Mach numbers for unducted concepts. Equation (3) $\eta_{pol} \sim 0.92$

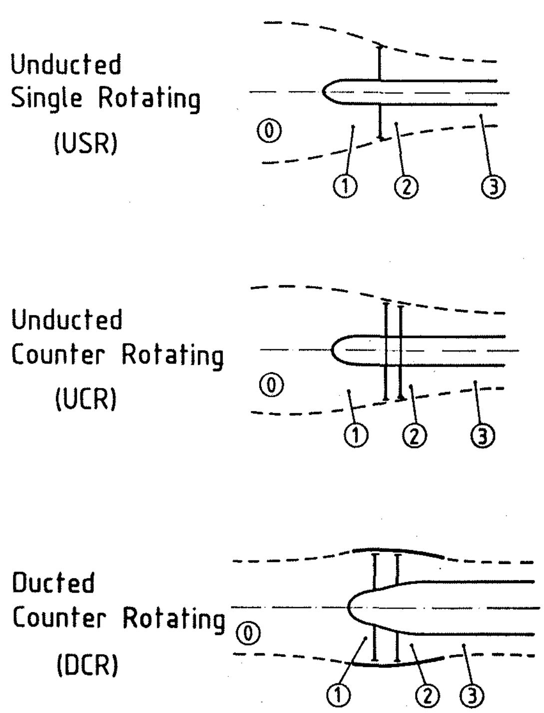


Fig.4 Propfan propulsion concepts

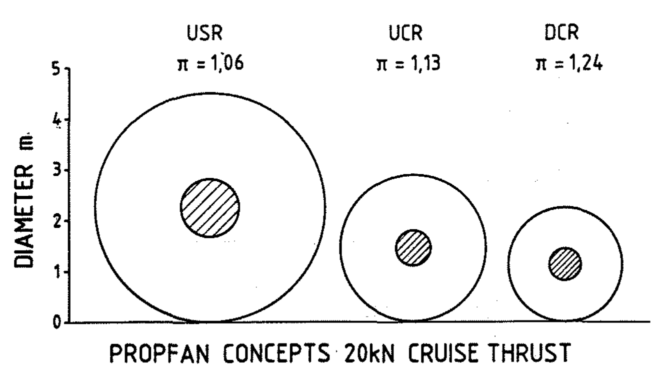


Fig.5 Survey of concept diameters

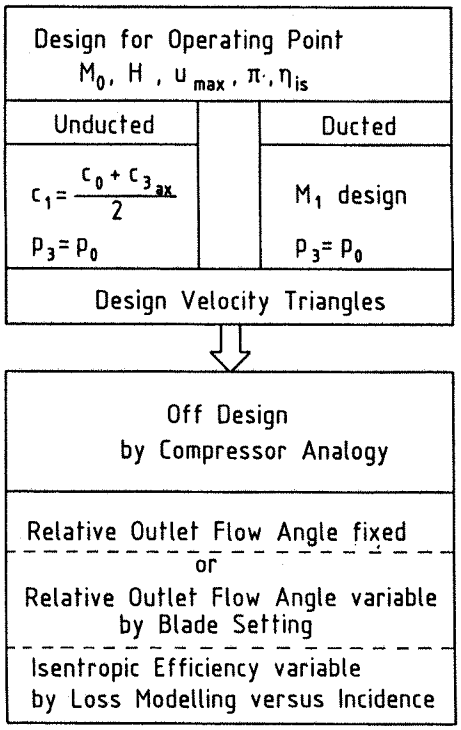


Fig.6 Computer program concept

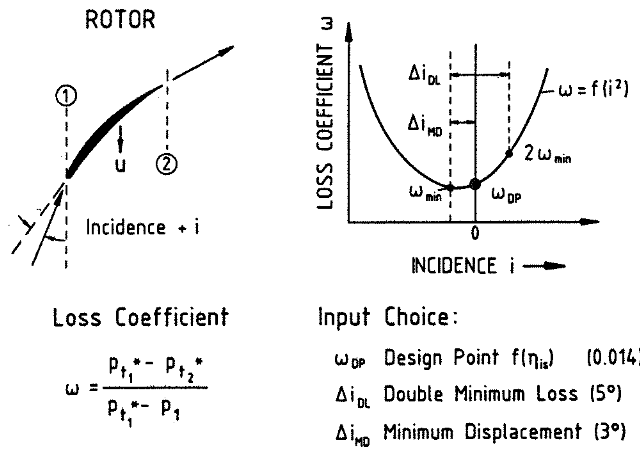


Fig.7 Modelling of rotor losses by a cascade equivalent loss coefficient

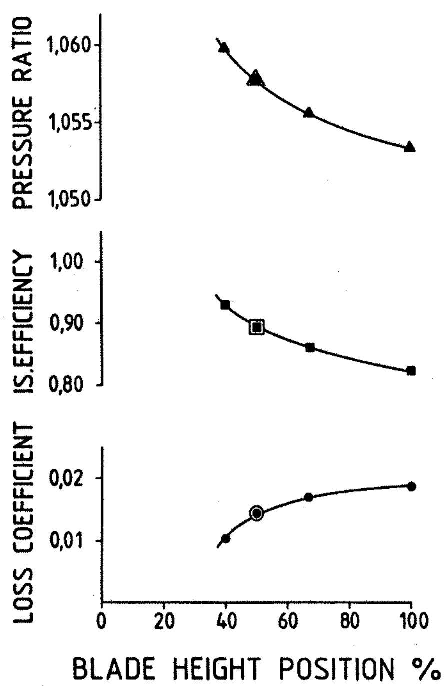


Fig.8 Influence of blade height position on average values

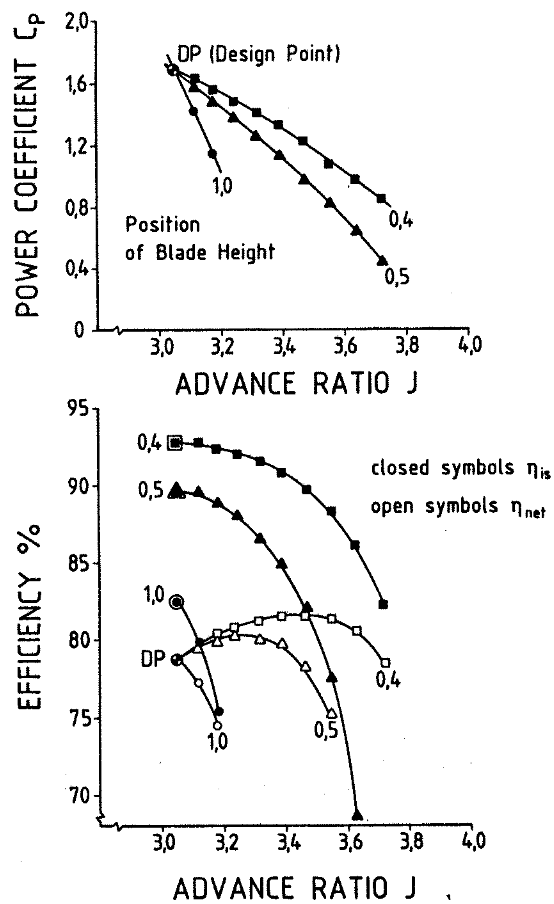


Fig.9 Off-design values depending on model blade height position

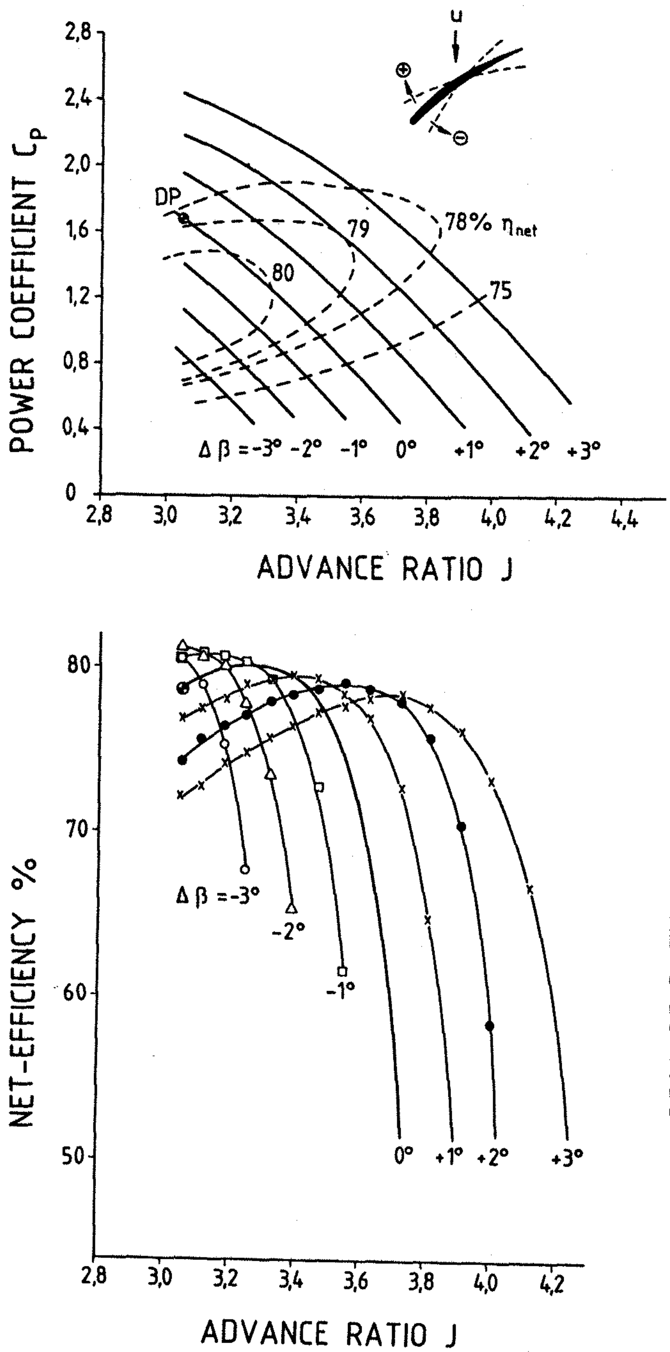


Fig.10 Calculated propeller performance characteristic of the USR concept at flight Mach number 0.8 (NASA SR3 basis)

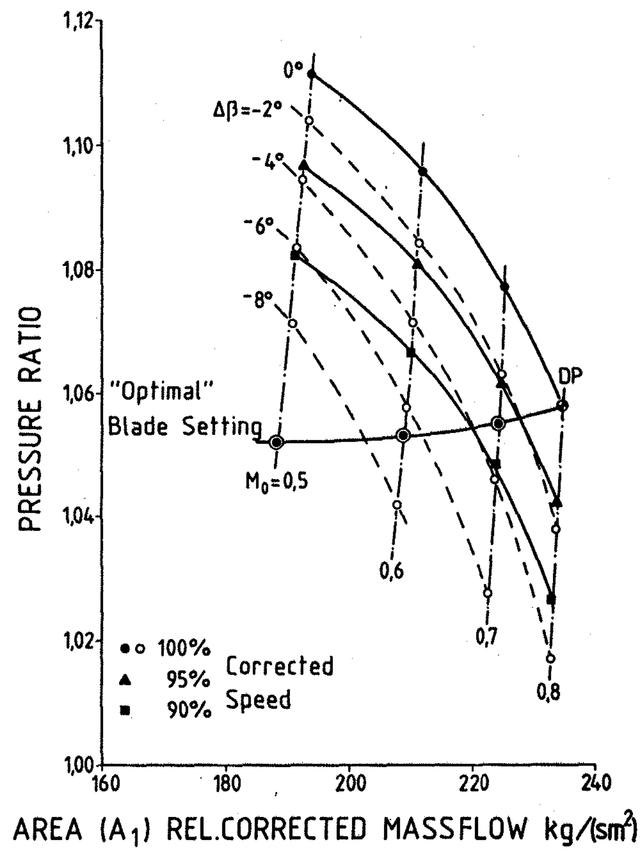


Fig.11 Equivalent fan-compressor performance characteristic of the USR concept with prescribed and optimal (◉) blade angle settings at 100% corrected speed

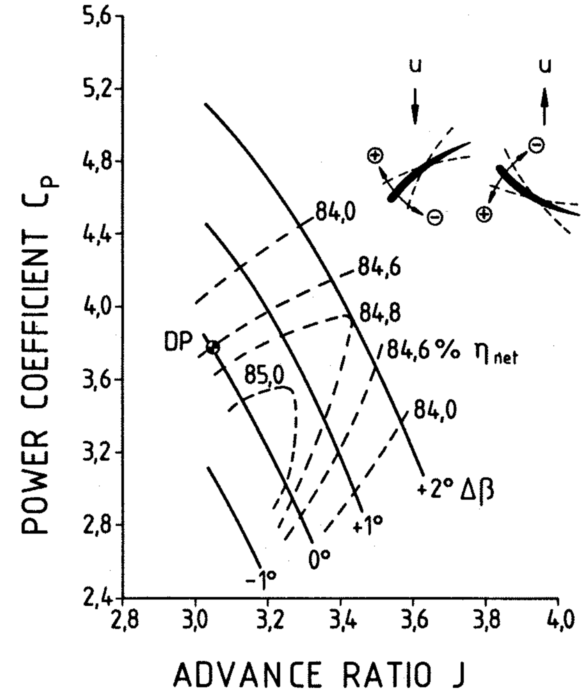


Fig.12 Calculated propeller performance characteristic of an UCR concept at flight Mach number 0.8

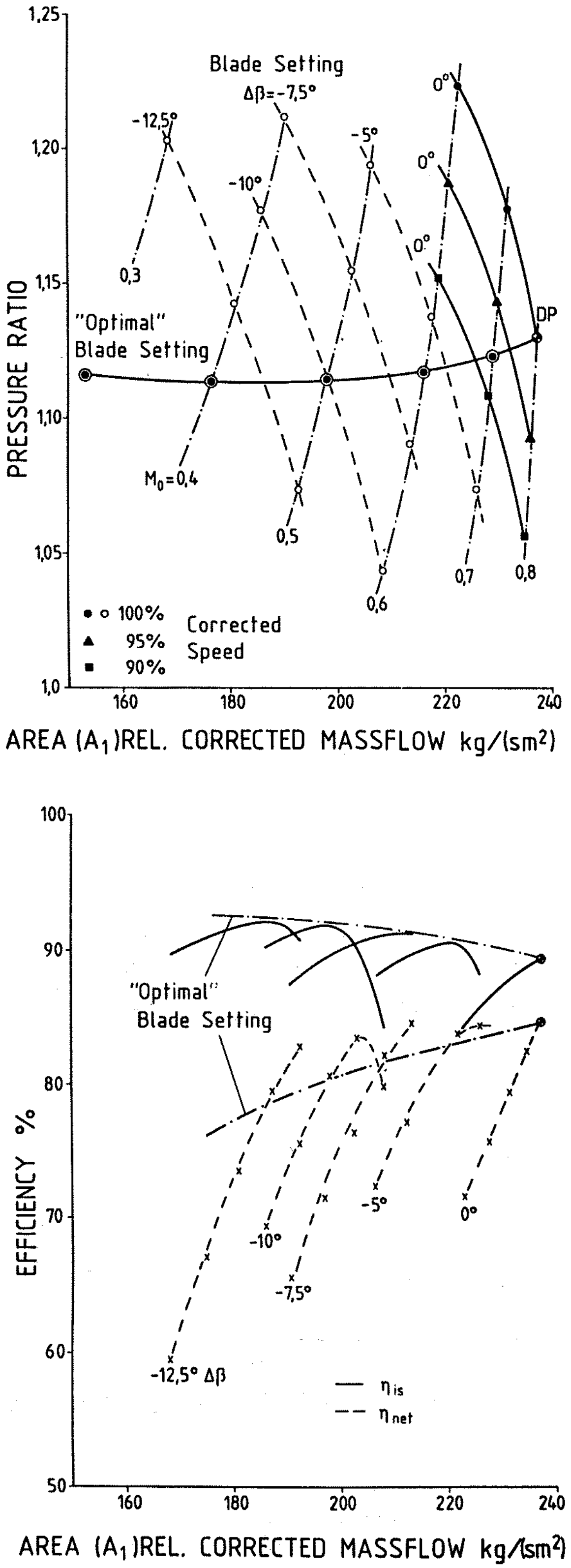


Fig.13 Equivalent fan-compressor performance characteristic of the UCR concept with prescribed and optimal (◉) blade angle setting at 100% corrected speed

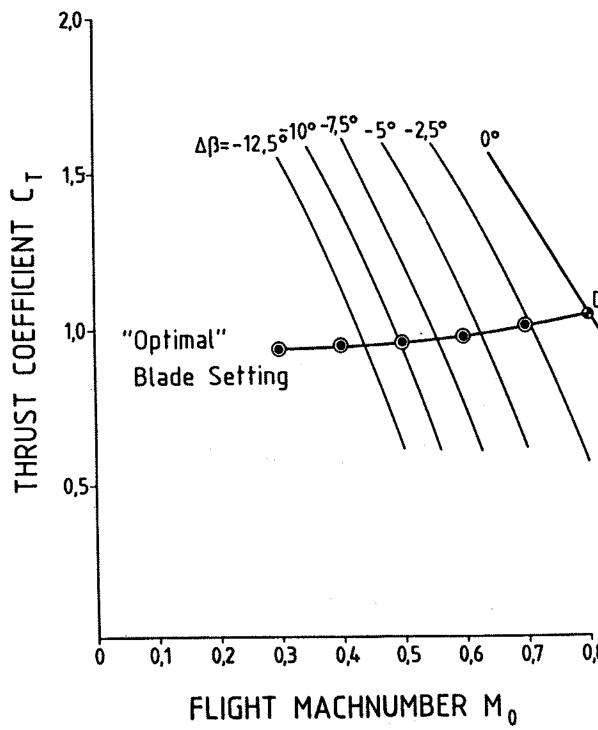


Fig.14 Thrust characteristic versus flight Mach number for the UCR concept (optimal blade setting at 100% corrected speed)

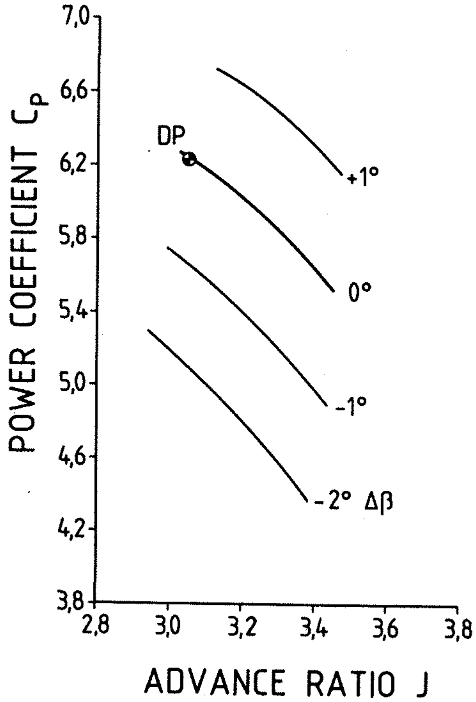


Fig.15 Equivalent propeller performance characteristic for the DCR concept

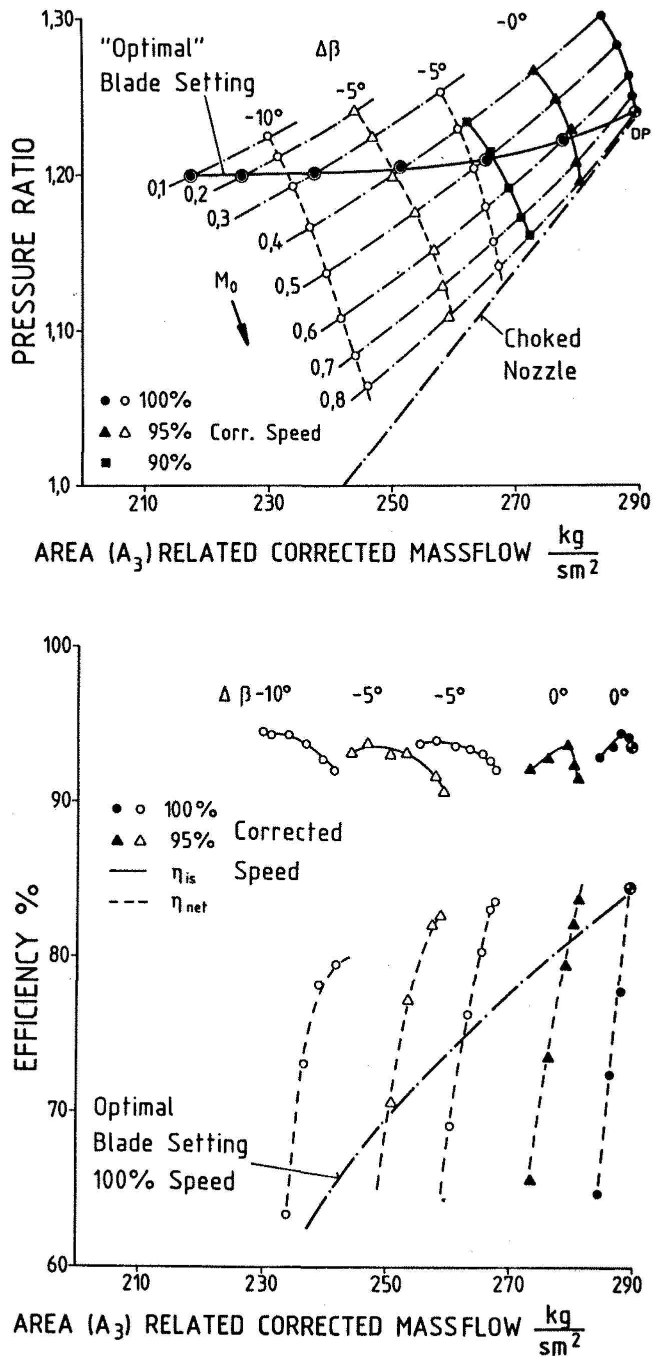


Fig.16 Calculated fan-compressor performance characteristic for the DCR concept with different prescribed blade angle settings and optimal blade setting at 100% corrected speed

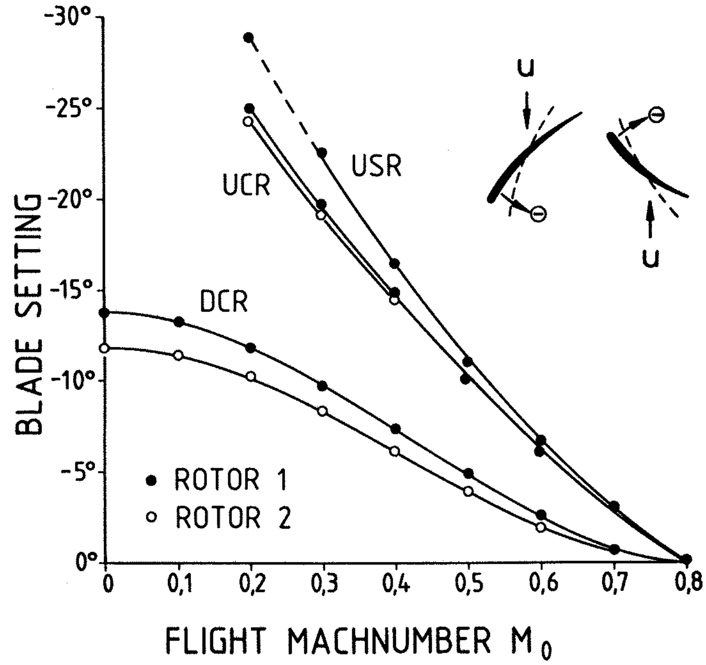


Fig.17 Optimal blade angle setting versus flight Mach number for all three simulated concepts at 100% corrected rotor speed