

# Analytic Design Methods for Wave Rotor Cycles

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A procedure to design a preliminary wave rotor cycle for any application is presented. To complete a cycle with heat addition there are two separate—but related—design steps that must be performed. Selection of a wave configuration determines the allowable amount of heat added in any case, and the ensuing wave pattern requires associated pressure discharge conditions to allow the process to be made cyclic. This procedure, when applied, gives a first estimate of the cycle performance and the necessary information for proceeding to the next step in the design process, namely, the application of a characteristic-based or other appropriate detailed one-dimensional wave calculation that locates more precisely the proper porting around the periphery of the wave rotor. Examples of the design procedure are given to demonstrate its utility and generality. These examples also illustrate the large gains in performance that might be realized with the use of wave rotor enhanced propulsion cycles.

## Nomenclature

$a$	= sound speed
$C_p$	= specific heat at constant pressure
$L$	= length of rotor channel
$M$	= Mach number
$m$	= mass
$P$	= "rightward moving" characteristic quantity, speed ( $u + a$ )
$p$	= pressure
$Q$	= "leftward moving" characteristic quantity, speed ( $u - a$ )
$q$	= heat (added or rejected) per unit mass
$R$	= gas constant
$s$	= entropy per unit mass
$T$	= temperature
$t$	= time interval
$u$	= fluid velocity (+ to right, - to left)
$w$	= cycle work per unit mass
$x$	= position along channel
$y$	= fraction of unit mass flow
$\gamma$	= specific heat ratio, 1.4
$\eta$	= efficiency
$\rho$	= density

## Subscripts

eft	= effective turbine inlet temperature
$s$	= refers to shock
$t$	= total or stagnation quantity
$x$	= quantity at engine exit
0	= ambient flight conditions

## Introduction

THE wave rotor is a device that provides direct energy exchange between gases. An introduction to wave rotor technology can be found in the literature.<sup>1-3</sup> An important

application of wave rotors is for gas turbine topping cycles, an idea that dates back to the early 1940s.<sup>4,5</sup>

The wave rotor improves the overall performance of a conventional engine by allowing the combustor exit temperature to be higher than the maximum allowable turbine inlet temperature. The performance of conventional gas turbine engines depends on the allowable operating temperature of turbine blade materials. Attempts to circumvent this limitation have renewed interest in wave rotor topping cycles.<sup>6-15</sup>

This article presents a design procedure for engine cycles utilizing a wave rotor to enhance cycle performance. Attention is paid in particular to the general features common to all wave rotor cycles. To demonstrate the procedure a few cycle examples are given with an estimate of their performance.

The discussion focuses mainly on the thermodynamic cycles possible utilizing unsteady flow. A "wave rotor cycle" refers to the thermodynamic engine cycle resulting from a wave rotor design. A "wave cycle" refers to a periodic unsteady flow pattern in the rotor channels. There is no "particular" or "best" cycle, but there are general features presented that all cycles must possess. It is these general features that are the subject here. Applying these general features allows one to design a particular wave rotor cycle for any given application and to estimate its performance. Other interesting applications for unsteady flows not involving heat addition also follow the general principles discussed here.

An unsteady flow cycle utilized for propulsion involves using shock waves to replace conventional compressors and unsteady expansion rather than conventional steady flow expansion in a nozzle. Shock waves driven by heat addition to the working fluid constitute a "wave turbine-compressor combination" that allows one to avoid the restrictions on peak temperature imposed by material properties that limit the performance of present day propulsion systems. The use of a wave rotor cycle results in a higher efficiency as well as an increase in power as compared with present cycles.

The wave rotor cycles treated here involve a wave rotor made up of straight constant area wave channels so that no shaft power is derived from the wave rotor itself. For the cycles discussed here the wave rotor is situated between the conventional compressor and conventional turbine.

The conventional compressor not only charges the wave rotor but is also used to flush it so a new wave cycle can commence. The conventional compressor is also the source of cooling air for the wave rotor which allows it to handle hot combustion gases. A conventional turbine is used where possible, intercepting hot flows issuing from the wave rotor chan-

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nels. The term "possible," implies in this context, a certain peak temperature for the turbine inlet that cannot be exceeded.

An unsteady expansion, as employed in a wave rotor, cools the flow isentropically as it would be cooled in a conventional turbine which extracts "enthalpy" from the flow, but does not require any blades. This has implications for the control of the  $\text{NO}_x$  emissions from engines.<sup>16,17</sup>

Comparison of wave engine cycles with conventional powerplant systems are conveniently made on the basis of  $T_{\text{eff}}$ .  $T_{\text{eff}}$  is defined as the turbine inlet temperature of the cycle that would be necessary to produce the same power in a conventional engine operating with ideal components (100% efficient compressor and turbine) in the maximum power mode. This mode requires the temperature leaving the ideal compressor to be equal to the square root of the product of the compressor inlet temperature and the turbine inlet temperature.  $T_{\text{eff}}$  is calculated by Eq. (1):

$$T_{\text{eff}} = (\sqrt{(w/C_p)} + \sqrt{T_0})^2 \quad (1)$$

It is assumed in this article that present engines can operate, at best, at 3000°R (1667 K); therefore, equivalent turbine inlet temperatures in excess of this are a measure of the improvement possible with wave rotor cycles.

In all cases the wave rotor cycles discussed will include shock wave losses. For all the calculations in this article,  $C_p$  is assumed constant and  $\gamma = 1.4$ .

### Wave Rotor Cycles

The general features of a wave cycle are shown in Fig. 1. The particular cycle portrayed is entitled "MINQ wave cycle." The essential waves are presented as a function of time as they progress through a single wave channel. A wave rotor is made up of a multitude of these channels arranged around a cylinder which is rotating at constant speed. Thus, the time in this diagram can be reinterpreted as an angle about the periphery of the wave rotor. An observer situated at a fixed angle at an open end of the rotor would observe a steady flow resulting from the unsteady cyclic flow in the channels going by. The flow velocity in the rotor is defined positive to the right. The discussion below concerns the necessary conditions to achieve an actual cycle.

There are generally eight regions of any cycle. To demonstrate the general wave cycle design procedure it will be

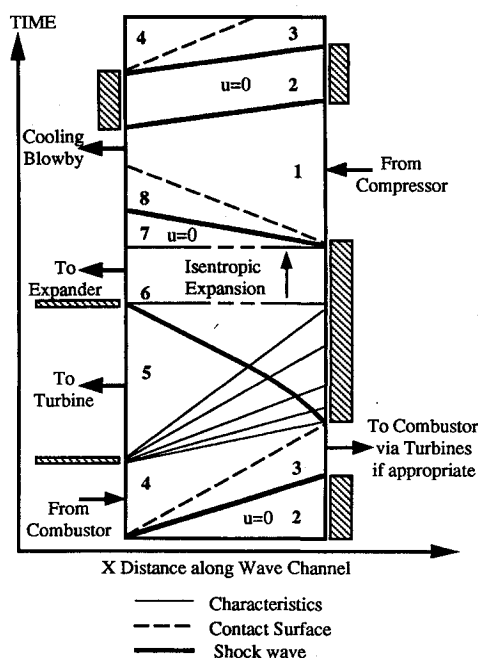


Fig. 1 MINQ wave diagram.

applied first to the MINQ cycle. Start with the introduction of air from a compressor in region 1. The compressor air sweeps out the residual gases, 8, by means of the shock wave between regions 7 and 8. These regions not only contain residual gases from the previous cycle but also residual waves (not shown). The shock wave clearly sweeps out the residual gases; to deal with the residual waves requires more discussion. The flow in region 1 is introduced at  $M = -1$ . This is desirable as the port size for a given flow is then the smallest. This also prevents wave disturbances from the rotor channel from reaching the compressor, and the waves remaining from the preceding events are trapped in the channel.

There are two types of waves in the channel, those moving with the velocity  $(u + a)$ , which we name  $P$  waves, and those moving with the velocity  $(u - a)$ , which we choose to call  $Q$  waves. What we have chosen to call "waves," in accord with popular usage, are the mathematical characteristics of the set of differential equations describing the conservation laws for the one-dimensional unsteady flow in the rotor channels, along which a Riemann invariant is constant. (In our case,  $P = 5a + u$  and  $Q = 5a - u$  are the invariants, if the ratio of specific heats of the gas is a constant and equal to 1.4.) In port 1 the  $P$  waves are not allowed to enter because  $u = -a$ , whereas the  $Q$  waves emanating from port 1 all have the same value of  $Q$ . After the compressor gas clears the channel it is in some cases desirable to allow some blowby to supply cooling where necessary. Note that the extent of this region of blowby is arbitrary. If the cooling blowby gases are routed through a turbine after leaving the wave rotor, the cooling effect in this ideal case is "free," in that it does not affect the ideal Brayton cycle efficiency.

A stationary sidewall (stationary sidewalls are shown as cross-hatched regions in Fig. 1) is imposed at the end of the channel to stop the blowby flow. This results in a hammer shock wave that brings the flow in the tube to rest (thick line between 1 and 2). The  $Q$  waves pass through this shock wave with little change in their value of  $Q$ . These  $Q$  waves then reflect off the wall as  $P$  waves of constant value, since at the wall  $u = 0$ , so  $P = Q$ . Since behind the shock wave both  $P$  and  $Q$  are constant and equal to each other, the flow is at rest in region 2.

A more detailed calculation using the mathematical theory of characteristics can be used to determine the actual shock wave strength and trajectory that varies along the channel in just the required manner to, in effect, sweep out the residual waves. An apt description of this particular hammer shock wave for those familiar with a popular video game is the "pac man shock." The pressure that must be supplied at the boundary at 7 to force these desired wave phenomena to occur depends on other details of the cycle. Any wave pattern may be reduced to a uniform flow (it need not be a zero velocity flow) with this "wave trapping" procedure.

The hammer shock wave that brings the compressor flow to rest has a strength that can be estimated if it is assumed that it returns with uniform speed. The strength of this shock can be found using Eq. (2), which relates the states before and after the shock in terms of the "shock wave Mach number,"  $M_{s1}$ :

$$\frac{u_1 - u_2}{a_1} = -\frac{5}{6} \left( M_{s1} - \frac{1}{M_{s1}} \right) \quad (2)$$

Solving Eq. (2) for  $M_{s1}$ , (note  $u_2 = 0$ ), provides an expression for the strength of the hammer shock:

$$M_{s1} = \frac{-1 - \sqrt{1 + 4(5/6M_1)^2}}{10/6M_1} \quad (3)$$

Recall that  $M_1 = -1$ ; therefore,  $M_{s1} = 1.76$ , giving a static pressure ratio rise of 3.47. The hammer shock acts as a "wave

diffuser." If the wave was isentropic, the pressure rise would be 3.58. Thus, the shock wave diffuser operates with an efficiency of 97%. Note that the "unsteady wave diffuser" with shock wave losses included increases the pressure more than a perfect steady-flow diffuser would.

The gas in region 2 is then subjected to another shock wave (2 to 3). This shock wave is produced when the side plate that stopped the flow ends, and hot, high-pressure combustion gas is introduced into the wave channel at the left side of the figure. The compressor gas is further compressed by a factor of about 4 by this shock wave. The wave rotor cycle thus provides a static pressure rise ratio of 12–15 above the pressure supplied by the conventional compressor. Note that the compression process is in two stages, mimicking the Oswatitch diffuser and avoiding the losses that would be incurred if only one larger shock wave were used.

A port on the right side (port 3) is situated to remain open while collecting the shock wave compressed gases. These hot compressed gases are then directed either to a turbine or directly to the combustor depending on the desired cycle. The conditions that determine the heat addition in terms of the shock wave strength are the continuity of pressure and velocity across the gas interface 3-4, along with accounting for the mass that is returned to create this shock wave. If heat is added at constant static pressure in the combustor and all the flow is returned to the wave rotor, the temperature ratio 4 to 3 is equal to the ratio of the port sizes 4 to 3, as is easily verified.

Equation (4) is a statement of mass conservation between the mass exiting at port 3 and the fraction  $y$  of that mass returning through port 4

$$u_4 \rho_4 t_4 = y \rho_2 L \quad (4)$$

where  $t_4$  is the time port 4 remains open. The mass of gas in the tube at station 2,  $\rho_2 L$ , is taken as the unit mass of the cycle. All of the fresh air charge at 2 exits the rotor at port 3. For this particular cycle (MINQ),  $t_4$  has been chosen such that the first  $P$  wave generated when port 4 is closed reaches the right end of the channel simultaneously with the 3-4 interface. This time is given by Eq. (5):

$$t_4 = \frac{L}{u_3} - \frac{L}{u_4 + a_4} \quad (5)$$

Across the gas interface  $u_4 = u_3$  and  $\rho_4 a_4^2 = \rho_3 a_3^2$ . Combining these relations with Eqs. (4) and (5) one finds the quadratic equation

$$\left(\frac{a_4}{a_3}\right)^2 + M_3 \frac{a_4}{a_3} - \frac{\rho_3}{y \rho_2} = 0 \quad (6)$$

Solving Eq. (6) for the sound speed ratio across the contact surface allows one to find the heat added in the combustor in terms of the strength of shock wave 2-3:

(MINQ)

$$\frac{a_4}{a_3} = \frac{-M_3 + \sqrt{M_3^2 + (4/y)(\rho_3/\rho_2)}}{2} \quad (7)$$

Naturally, the shock wave strength is determined by the heat addition. For computational purposes, it is easier to assume the shock wave strength and solve the last equation for the temperature rise across the combustor.

The closing of the port at 4 is immediately followed by the opening of exhaust port 5 to a lower pressure causing an unsteady expansion that reverses the flow. The static temperature change from 4 to 5 is given by

$$\frac{T_5}{T_4} = \left[ \frac{5 - M_3(a_3/a_4)}{5 - M_5} \right]^2 \quad (8)$$

Since the expansion wave is unsteady there is a decrease in both total temperature and total pressure from 4 to 5. The total temperature of the flow, processed by this expansion, decreases by at least a factor of 5/6 (if  $M_5 = -1$ ). For temperatures near 3000°R (1667 K) this means this expansion reduces the temperature out of the combustor by at least 500°R (278 K). Until the weak shock formed by the closing port 3 returns to the left side of the channel, the flow out of port 5 is steady and an axial turbine might be situated to intercept this flow.

The amount of mass exiting at port 5 depends on the time it takes this shock wave to return to the left side of rotor. By solving the differential equation for the trajectory of this wave, assuming it is weak, an expression for the time port 5 is open  $t_5$  is found:

$$\frac{t_5 a_2}{L} = \left( \frac{5 - M_5}{5 - M_4} \right)^3 \frac{2}{(1 + M_4)(1 - M_5)} \frac{a_2}{a_4} \quad (9)$$

This result is used to calculate the mass leaving the rotor at port 5 with respect to the reference mass at station 2 ( $m_2 = \rho_2 L$ ):

$$\frac{m_5}{m_2} = \frac{p_3}{p_2} \left( \frac{5 - M_4}{5 - M_5} \right)^6 \left( \frac{t_5 a_2}{L} \right) \left( \frac{a_2}{a_4} \right) (-M_5) \quad (10)$$

Similarly, the amount of energy leaving the wave rotor at port 5 can be calculated to estimate the amount of work that can be extracted in a conventional turbine receiving this steady flow.

The pressure at 7 must be chosen to accommodate the required shock wave 7 to 8 that flushes the channel and sets up the flow that traps the waves so the cycle can be completed. The wave pattern in the channel is tending toward a uniform zero velocity condition as region 7 is approached, and so we neglect the kinetic energy term in region 7 in this approximation and assume the processes occurring from 6 to 7, the "To Expander" region of Fig. 1, are isentropic. This module of the calculation depends on the first module describing heat addition, only through the total entropy change to 7. The shock strength  $M_{s7}$  is found by the following procedure. Using the boundary conditions at the gas interface between 8 and 1,  $u_8 = u_1$  and  $p_8 = p_1$ , and the shock wave relations between states 7 and 8, an expression for  $(a_7/a_1)$  can be found:

$$\frac{u_8}{a_7} = -\frac{5}{6} \left( M_{s7} - \frac{1}{M_{s7}} \right) = \frac{u_1}{a_1} \frac{a_1}{a_7} = -\frac{5}{6} \frac{M_{s7}^2 - 1}{M_{s7}} \quad (11a)$$

and so

$$\frac{a_7}{a_1} = (-M_1) \frac{6}{5} \frac{M_{s7}}{(M_{s7}^2 - 1)} \quad (11b)$$

and from normal shock relations

$$\frac{p_8}{p_7} = \frac{p_1}{p_7} = \frac{7M_{s7}^2 - 1}{6} \quad (11c)$$

For  $\gamma = 1.4$ , the entropy change from 7 to 1 is

$$\frac{s_7 - s_1}{R} = 7 \ln \frac{a_7}{a_1} - \ln \frac{p_7}{p_1} \quad (11d)$$

By combining Eqs. (11b)–(11d) an expression for  $M_{s7}$  is found:

$$\frac{M_{s7}^7 (7M_{s7}^2 - 1)}{(M_{s7}^2 - 1)^7} = \frac{5^7}{6^6} \frac{1}{(-M_1)^7} \exp[(s_7 - s_1)/R] \quad (11e)$$

The principles discussed so far are sufficient to describe any wave rotor cycle with wave trapping, and have been applied



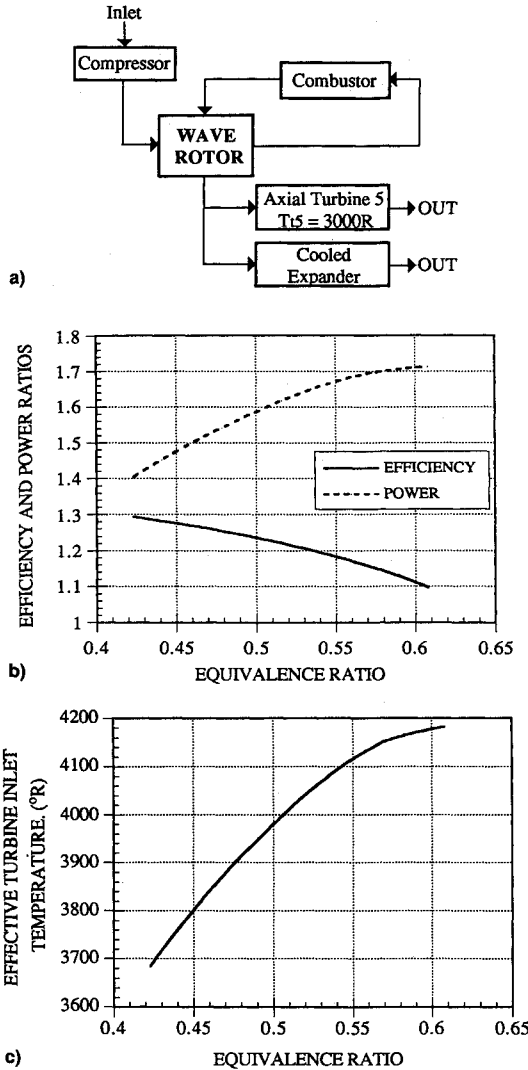


Fig. 3 Helicopter a) block diagram, b) efficiency and power ratio curves, and c) effective turbine inlet temperature.

previous cycle all the power produced is via a shaft as might be desirable for helicopter applications.

For comparison purposes choose a maximum power Brayton cycle as mentioned in the Introduction. Efficiency ratio, power ratio, and effective turbine inlet temperature are quantitative measures used to compare the wave cycle performance with that of the ideal maximum power Brayton cycle. The efficiency ratio is defined as

$$\text{eff ratio} = \frac{\eta_{\text{wave cycle}}}{\eta_{\text{Brayton}}} \quad (18)$$

and the power ratio is

$$\text{pwr ratio} = \frac{(w/C_p)_{\text{wave cycle}}}{(w/C_p)_{\text{Brayton}}} \quad (19)$$

The effective turbine inlet temperature was defined in Eq. (1). By comparing ideal cycles it is expected that real cycles might scale in the same ratios.

The performance curves for helicopter are shown in Figs. 3b and 3c. Note the large gain in performance possible using the wave rotor cycle.

#### $M = 0.8$ Transport

Next, a rotor cycle is treated that might be appropriate for subsonic flight conditions appropriate to modern day trans-

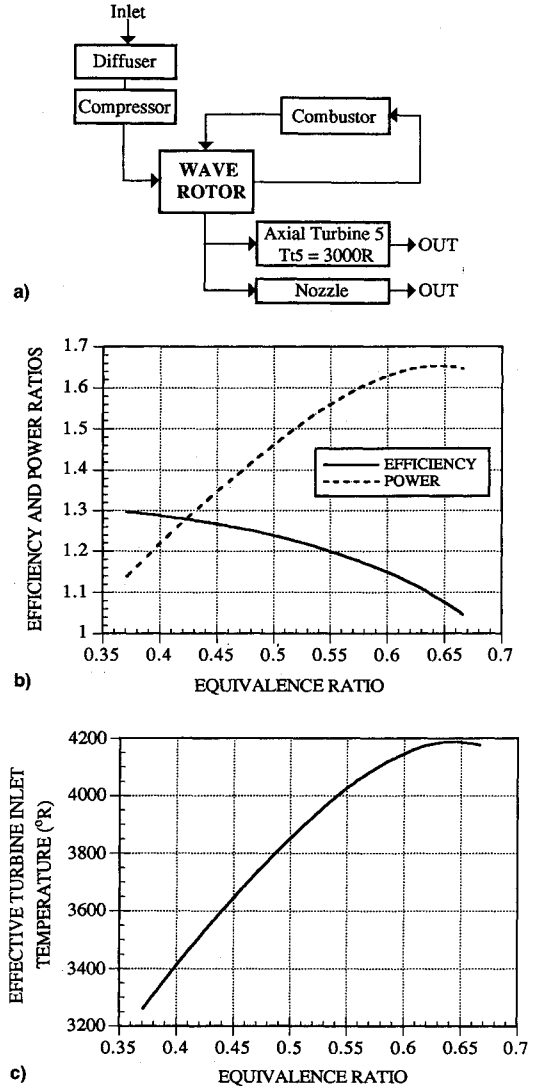


Fig. 4 Subsonic transport a) block diagram, b) efficiency and power curves, and c) effective turbine inlet temperature.

ports. The cycle schematic is shown in Fig. 4a. In this case the flow issuing from port 5 is again utilized in an axial turbine. In the case considered, the work from this axial turbine is more than sufficient to power the conventional compressor that feeds and purges the wave rotor channels.

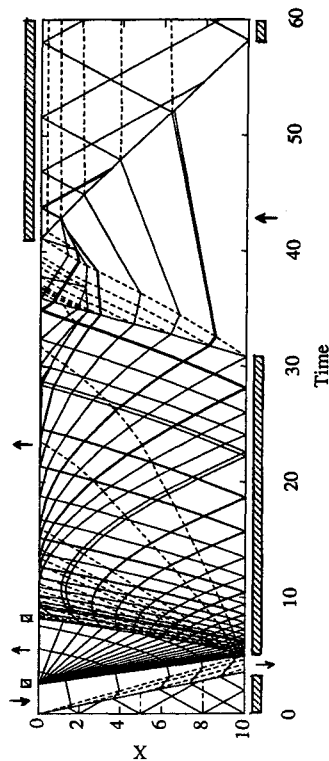
In this cycle the flow in the expander region is utilized in a jet thrust nozzle and there is no need to utilize the cooling blowby flow. The unsteady process in the wave rotor expansion allows the nozzle and turbine drive temperature to differ by more than  $800^{\circ}R$  ( $444\text{ K}$ ) with the nozzle receiving the hotter flow. This is not possible in a conventional engine unless after-burning, with its associated losses, is used. Since the turbine inlet temperature is within our chosen limits, no cooling in addition to the conventional blade cooling required to reach  $3000^{\circ}R$  ( $1667\text{ K}$ ) is required in this cycle.

The advantages gained are slightly larger than in the previous case, as can be seen in Figs. 4b and 4c. Again, the improvement from utilizing wave rotor cycle technology is large and indicates the desirability of exploring further the possibilities. Associated noise and propulsive efficiency considerations are not considered.

Figure 5 is a computer-generated wave diagram for the subsonic transport case where the total pressure ratio of the conventional compressor is 21.48. This cycle is a MINQ cycle. The port data used to generate the computer diagram is given in Table 1. The pressure used for port 7 is the value calculated via the procedure outlined in the Cycle Overview section. This is a specific example of the use of analytical calculations

**Table 1** Subsonic transport boundary conditions

Description	$T, R$	$p, \text{atm}$	$M$
Flight conditions	400	0.185	0.82
Port 1	801	2.10	-1
Shock (2-3)			2.778
Port 3	2926	64.4	1.293
Port 4	5474	64.4	0.945
Port 5	2500	4.14	-1
Station 7	1583	0.838	
Shock (7-8)			1.514
Port 8	2105	2.100	-0.62

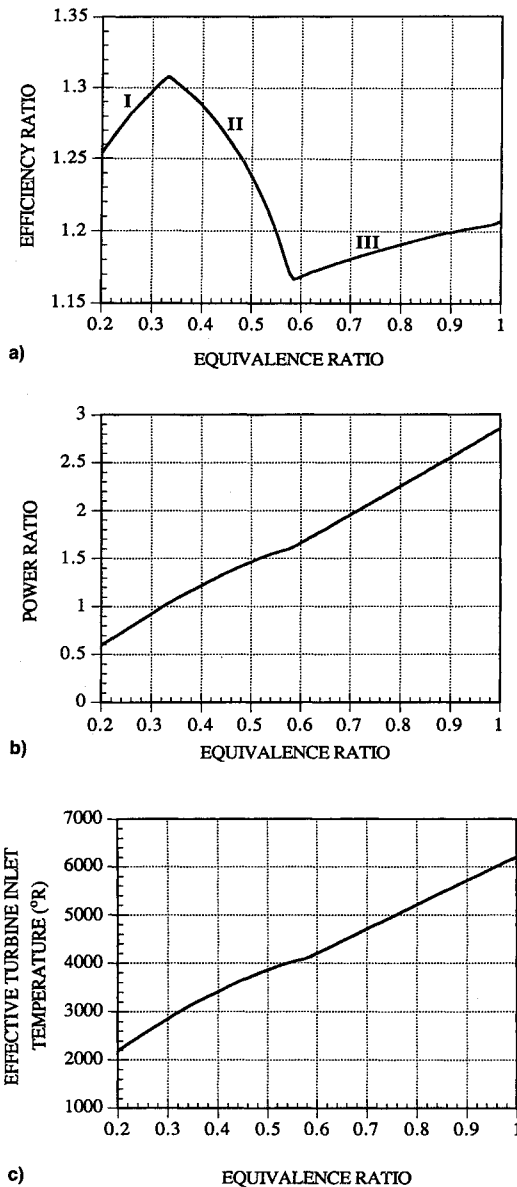
**Fig. 5** Computer generated wave diagram for subsonic transport case.

to provide the necessary boundary conditions for a more detailed computer model of the cycle.

#### Supersonic Transport

The final example presented is a case similar to the subsonic transport in cycle geometry, but for a supersonic flight Mach number of 2.5, flying at an altitude of 60,000 ft. Because the ram pressure in this case is considerable, the possibilities are even more impressive than in the subsonic case. The range of equivalence ratios possible in this case extends all the way to stoichiometric.

The performance is summarized in Figs. 6a–6c. There are three ranges of operation (I, II, III in Fig. 6a). At low power, (I), the drive turbine situated at port 5 is sized to drive the conventional compressor required to purge the combustion products. At intermediate equivalent ratios, (II), there is more than sufficient power in the gas leaving port 5 and entering the turbine to drive the required conventional compressor. The required conventional compressor is small at low power, increases until the turbine blade temperature limit forces more wave compression and a resulting decrease in the pressure ratio required of the conventional compressor, until finally the conventional compressor is not needed at all (III). In this stage the wave rotor cycle operates with ram and wave compression only. Over the entire operating range the performance of the cycle is more efficient and supplies more power than possible with current technology.

**Fig. 6** Supersonic transport a) efficiency ratio curve, b) power ratio curve, and c) effective turbine inlet temperature.

#### Conclusions

A convenient design procedure that, if followed, insures workable wave rotor cycles, has been presented. The essential features of any propulsion cycle are outlined and several examples are presented to demonstrate the procedure and quantify the possible gains to be realized with rotor enhanced power cycles.

The initial design procedure provides the basis for a more detailed analysis for coupling the wave rotor to other power producing components. In this article a possible turbine blade operating temperature of 3000°R (1667 K) is assumed, although wave rotor enhancement of power cycles can be realized whatever the assumed turbine blade temperature. In wave rotor cycles the turbine blades are not subject to the highest temperatures of the cycle, allowing combustion chamber technology to be decoupled from the turbine blade performance.

The gains possible using wave rotor technology are considerable resulting in increases of power by a factor near 2, coupled with better efficiencies as compared with current practice. The versatility of the cycles discussed seem to open new possibilities for this technology, which if exploited would provide more efficient and powerful propulsion systems.

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