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POWER PLANT

Interaction Between Thrusters, Power Systems, and DP Control Systems

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Interaction Between Thrusters and the Power System

Introduction

This section discusses the interaction between the state-of-the-art thruster for large DP vessels: a thruster with fixed-pitch propeller, driven by an A. C. motor which is controlled by a variable speed drive (VSD), and the power system. Focus is placed on the operation of the thrusters for optimum fuel efficiency and the importance of the right selection of the propeller design point for the optimum performance of the propeller in multi-duty applications (e.g., stationkeeping, as well as transit operation).

The typical variable speed drive system allows the thruster to operate below the propeller design point[1] up to the design torque value and from the design point up to the full (vessel-) speed up to the nominal power value. In other words, if the propeller design point is selected for six knots inflow velocity, the propeller can be operated between bollard pull and six knots up to its maximum torque; at six knots inflow velocity the propeller can be operated at its design values for torque, power, and rpm. Above six knots inflow velocity, the variable speed drive system is able to increase the base speed of the motor by weakening of the motor field. This changes the characteristic of the drive motor; it allows increased rpm but is limited to the maximum power rating. The torque is reduced by the rpm increase. The range of this field weakening operation is limited by the design of the motor and the VSD and is typically approximately 10-20% of the base rpm.

A motor/drive system designed for a base speed of 1200 rpm and 20% field weakening can be operated to its torque (current) limit between 0 and 1200 rpm, and to its power limit from 1200 rpm to 1440 rpm. This feature needs to be considered in the optimization process of the propulsion system. Obviously, the design of the thruster is also affected by this feature. The mechanical design of the thruster should be carried out in such a way that an operation at a certain speed above the nominal speed is feasible in order to achieve an optimized propulsion system.

Selection of the Propeller Design Point

The selection of the propeller design point depends on the mission of the thruster, i.e., on its operational profile. Three distinct categories of thruster applications are found in offshore operations:

[1] The design point is the condition in which all propeller parameters including power, torque, rpm, and the inflow velocity are at their nominal or rated values.

- Thrusters used for stationkeeping only
- Thrusters used for stationkeeping, and low-speed propulsion, i.e., thrusters installed on semi submersible units providing thrust for DP operations and transit operations at lower speeds (6-8 knots)
- Thrusters used for stationkeeping of DP drillships providing thrust for DP operations, as well as transit operations at speeds of 12-14 knots

Stationkeeping only: This thruster operates typically in inflow velocities between zero knots (bollard pull) and maximum four knots. The propeller for this thruster should be designed for bollard pull, with a 10% field weakening/rpm increase capability. This thruster can be operated in its full operating range up to full power without overloading any of its components in torque, power, or rpm. This arrangement yields the highest possible performance for stationkeeping. With increasing inflow velocity, the propeller rpm will be increased to deliver optimum thrust up to the power limit. Due to the characteristic of the propeller, however, the thrust at increased inflow velocities is lower than the bollard pull, even at maximum power operation. The exact thrust values can be calculated for the particular propeller design. For most thrusters in DP applications, the reduction of thrust during inflow velocities is approximately 7% per knot.

Stationkeeping and low speed transit speeds: The design of this thruster – typically used on a DP semisubmersible - depends on a small extent on the preferences of the owner. As mentioned above, for optimum bollard pull performance the thruster should be designed for zero knots. However, moving the design point slightly higher, i.e., to two or three knots, slightly improves the transit performance by reducing the stationkeeping performance only marginally.

Stationkeeping and transit speeds of 12 – 14 knots: This scenario is typical for the new generation of super DP drillships and other offshore vessels with similar propulsion duties). The size of the propulsion system is typically determined by the stationkeeping duty, and needs to be as fast as feasible to utilize their higher degree of mobility in comparison with a semisubmensible. The question is: where is the optimum design point of the thruster propeller to satisfy the mission requirement for transit, as well as for stationkeeping with a minimum of sacrifices in both missions.

The following presents a trade-off study for a modern DP drillship. The mission of this vessel includes drilling in DP mode and transit at 14 knots. The study investigates in detail the propulsion performance at various design parameters and concludes that the optimum design point for the propeller is at six knots inflow velocity. The thrusters used for the study are Kamewa-Aquamaster 7000 Model, which are widely used on large DP vessels.

The calculations represent the theoretical performance of the propeller and the nozzle only. They do not account for any reduction in thrust or propeller/nozzle efficiency due to the presence of the thruster gear housing, support struts, etc.

Table 1 shows the summary of the results of the propeller optimization calculation:

- The highest bollard pull values can be achieved by designing the propeller for zero inflow. The thrust of this propeller at 14 knots is 10% lower than of that designed for 13 knots. An rpm increase of more than 15% is required to operate this propeller at full power at 14 knots.

- Designing the propeller for 13 knots yields the highest thrust at transit speed but reduces the thrust available at bollard pull by 10%. Rpm increase for 14 knots transit speed is negligible.

  - The listed values for design points 2, 4, 6, and 8 knots indicate feasible compromise designs. Reviewing the results of the calculations, the inflow velocity of 6 knots is evaluated as the suggested optimum propeller design point:

    - Bollard pull is marginally reduced (approximately 1.5%)

    - Thrust at 14 knots is 6% higher than that of a propeller designed for bollard pull

    - Rpm increase for full power at 14 knots is 12%, an increase which should be accommodated by the thruster manufacturer

    - Maximum motor output at bollard pull is 4804 kW

Table 1
Selection of the Propeller Design Point

Propeller Design Point (Knots)	**0**	**2**	**4**	**6**	**8**	**13**
Max. BP thrust (kN) [1]	889.7	889.4	888.3	877.4	864.5	806.3
Max. power PD (kW) at BP [2]	4750	4724	4668	4564	4461	4009
Max. motor output (kW) at BP (at torque/current limit)	5000	4973	4914	4804	4696	4220
Propeller rpm at BP	151.0	150.2	148.5	145.1	141.9	127.5
BP thrust in % of BP thrust at BP design point	100.00	99.97	99.84	98.62	97.17	90.63
Thrust at 14 knots (kN)	347.0	355.0	362.5	368.5	373.0	383.0
Thrust at 14 knots in % of thrust at 14 knots at BP design point	100.0	102.3	104.5	106.2	107.5	110.4
Propeller rpm at 14 knots, full power	174.2	172.8	171.6	168.6	166.4	154.1
Required rpm increase at 14 knots and full power in % of design rpm (151 rpm)	115.4	115.0	113.6	111.7	110.2	102.1
Motor output power (kW) at design point	5000	5000	5000	5000	5000	5000
Power PD (kW) delivered to the propeller at design point	4750	4750	4750	4750	4750	4750
Propeller rpm at design point	151	151	151	151	151	151

Notes: [1] BP = bollard pull or thrust at zero inflow velocity
[2] PD = power delivered to the propeller = 0.95 x motor output power

Thruster Operation

This section pertains to the operational interaction between the thruster, the thruster drive system and power system. The objective of this section is to develop guidelines for efficient thruster operation for thrusters with CP propellers and for thrusters with FP propellers.

The propulsion system of a DP vessel is sized to provide stationkeeping forces for the most severe operating scenario specified by the owner or operator of the vessel. During most of its operating time, the DP vessel operates in environmental conditions which are far less severe than the ones used as the design basis for the power and propulsion system. As a result, during the majority of its operating time, the DP vessel operates the propulsion system at partial load. The power system is typically equipped with a multiple installation of Diesel-generator sets; the number of generators on-line is selected (mostly automatically by the power management system) according to the power demand of the vessel. As a result, the engine generators operate at relatively high loads, at conditions of optimum fuel efficiency.

The propulsion system consists of a multiple installation of thrusters. During most of its operational time, only a part of the installed thrust capacity is required. The operator has two basic choices:

- Operating all thrusters at the required low load or
- Operating a few thrusters at high load

The following pertains to the recommended operating scenario for thrusters with FP, as well as thrusters with CP propellers. The recommendations focus on efficiency of the operation; other considerations of thruster operation (such as redundancy) must be evaluated on a case-by-case basis. To simplify the subject, only bollard pull (zero inflow or current speed) conditions are discussed; however, the principles of the operation are similar for stationkeeping operations at current speeds.

Operation of a Fixed Pitch Propeller

During bollard pull operation, the actual efficiency of a propeller is zero. For this reason, the thrust per power unit (specific thrust) is used as a substitute value. In theory, thrust is generated by a propeller by accelerating the fluid in which it works. It is equal to the change in momentum. More about this subject in the chapter ***More Thrusters at Lighter Load for More Efficiency*** by Howard Shatto.

During bollard pull operation, the propeller thrust is a function of the propeller diameter, the propeller rpm, the density of the water, and the thrust coefficient . This coefficient is specific for the particular propeller blade design and is a constant for bollard pull operation. During bollard pull, there is a simple direct mathematical relationship between the above listed values. Figure 1 shows a calculation for the propeller thrust as a function of the propeller power and indicates that the specific thrust (thrust/power ratio) increases asymptotically with decreasing power. This simply concludes that the specific thrust increases with decreasing load.

For the operation of the DP vessel, the above conclusion is that the operation utilizing all thrusters at the lowest possible power level yields the highest thrust per input power.

Fuel Cost Savings

Following the above conclusions, it is obvious that the operation of a thruster at lower load levels results in lower fuel costs per generated thrust than the operation of a thruster at full thrust. The following example demonstrates this fact and is presented in Figure 2. This graph shows the fuel consumption of a large DP drillship equipped with 6x5000 kW thrusters. The left column represents the annual fuel costs operating the vessel at 50% thrust load, generating this thrust by operating three thrusters at 100% thrust load; the middle column represents the fuel costs for the same thrust requirement, but operating all six thrusters at 50% thrust load and the right column represents the difference between the columns – a cost saving of $1.74 million per year. This graph should be used only to demonstrate the cost impact of the thruster operation options. Many other factors need to be considered in order to reach the right decision during various operational conditions

Mechanical Aspects

The mechanical aspects of operating multiple thrusters at lower loads are minor, but should not be ignored. In order to keep an azimuthing thruster ready, several auxiliary systems have to operate, such as the hydraulic azimuth system, its cooling system, the thruster lubrication system, and the main drive motor cooling system. The variable speed drives on-line also have to operate their auxiliary systems, mainly the cooling systems. Altogether, these systems use some power, which amounts to a small (2-3) percent of the installed power.

The azimuth gear, including seals, as well as the propeller shaft seals will be subjected to wear; other mechanical components such as gears and bearings operate at low load levels and cause a minimum of wear.

Operation of a Propeller with Controllable Pitch (CP) Propeller

The advent of variable speed drive systems for AC motors provided the offshore industry the feasibility to utilize mechanically simpler and consequently more reliable thrusters with fixed pitch propellers for high power applications. Prior to the availability of VSD AC systems, the SCR controlled DC motor with shunt field was the only electrical drive which allowed rpm control from zero to full speed. Limitations in voltage limited the DC systems to approximately 3000kW per drive. Most of the higher, as well as many smaller thrusters, were equipped with constant speed electric AC drives; the control of thrust was achieved by varying the pitch of the propeller[2]. Very few newly built offshore units are equipped with CP propellers, but many CP propeller thrusters are in operation which are addressed in this chapter.

The basic hydrodynamic principles apply to the CP propeller, as well as to the FP propellers; however, the operation of the typical thruster CP propeller is different and causes thrust losses during low-load operations. The CP propeller operating at constant rpm consumes energy to overcome the friction losses of the propeller blades over the entire operating range, even during a blade position for zero thrust, whereas the friction losses of a FP propeller are zero at zero thrust (and zero rpm). As a result of that, the CP propeller is far less efficient in the lower thrust range than a FP propeller. Figure 3 compares the power requirements of both propeller types as a function of the propeller thrust. The CP propeller consumes 18% of its rated power at zero thrust while the FP propeller consumes zero power at this point. The two performance curves merge only at the full thrust point. Differences at this point are marginal and are, therefore, neglected. The 18% point is an actual value measured on a recent installation and is a very conservative figure. Increase of the surface roughness of the propeller blades, wear from cavitation, fouling by marine growth, minor blade damages, etc. contribute to an increase of this 18% value over time (up to 40% are recorded). This zero-thrust power requirement is also a function of the propeller design. Typically, propellers designed and optimized for bollard pull with a large propeller cause a higher amount of zero-thrust losses.

Fuel Cost Savings

Figure 4 shows several fuel consumption scenarios for thrusters with CP propellers. It is based on the very conservative figure of 18% power requirement at zero-thrust as described above. During operation at 50% thrust level, a similar effect can be seen as in Figure 2 for the FP propeller; the difference and the resulting fuel cost savings, however, are less than half of the ones for the FP propeller. With increased reduction in thrust, the situation becomes worse, culminating in Column 4, showing the annual fuel costs for an operation of 6 thrusters at zero thrust to be $2.2 million. (This is, of course, a hypothetical figure, only mentioned to emphasize the point. A thruster with FP propeller, in comparison, would consume practically zero fuel).

Conclusion

For fuel efficient operation during partial thrust loads, a vessel equipped with FP propeller thrusters should operate the highest number of thrusters available. In particular,at thrust demands below 50%, the vessel equipped with CP propeller thrusters should operate a minimum number of thrusters. The actual number of CP thrusters on-line must be governed also by other factors, such as redundancy, rapid thrust availability, etc.

[2] Specifically in Europe, some installations utilized two-speed AC motors. The above discussion addresses CP propeller only driven by constant rpm AC motors.

Interaction Between Thrusters and the DP Control System

Introduction

The environmental elements, such as wind, current, and wave drifts generate forces and moments on the vessel. The thrusters have to generate counter forces and moments to create a force and moment equilibrium. The thrust allocation logic of the DP controller calculates the magnitude and direction required for each thruster to establish a counter

The closed-loop DP control system for an FP propeller thruster faces a problem in that the ideal control would be to control the force generated by each thruster and to use a measurement of the force as the feedback. It is, however, not feasible to directly command force (thrust) or to measure thrust and use it as a feedback signal.

The thruster with CP propeller operating at constant speed is limited to the pitch angle as the control value; the drive motor power is used in addition in many cases. In the case of FP propeller thruster driven by an VSD, the only control value is the thruster rpm. Many DP systems use the rpm also as the feedback value. Optional values which can be used as feedback signal are motor torque (current, Amps) or motor power (kW). The following section describes some of the features and differences applying these feedback values.

The DP systems designed in the last 30 years include all three feedback options, although the rpm feedback is the most widely applied.

Control Feedback

Propeller rpm is the control value most often applied in DP systems. Rpm can be easily and accurately measured. Unfortunately, it also introduces, in some areas of the control, the highest rate of error.

Only at bollard pull, i.e., in a condition without current velocity and no vessel movement, the propeller operates at a fixed relationship between rpm and torque (and, consequently, power). Knowing one of the values (e.g., rpm) determines the other (thrust, torque, power). However, when the vessel is moving to correct position, to execute yaw maneuvers, etc., or is in the presence of current, the relationship of rpm, thrust and current changes with the velocity of the motion of the vessel or current. At a relative motion of four knots (although this case may be considered to be extreme, it is a realistic situation e.g., a loop current in the Gulf of Mexico), this relationship is no longer true. Another parameter is introduced into the relationship between power, thrust or torque, and rpm, in the form of the inflow velocity. Figure 5 shows the relationship of thrust, torque, power and rpm. The curves for torque and thrust overlap, and both are a function of the second power of the rpm. Controlling rpm and programming the relationship of the rpm with the thrust establishes an exact set point for thrust[3]. During zero inflow, the accuracy of the control is not affected whether rpm, torque, or power is used as the set point command.

Figure 6 shows the relationship between power, rpm, torque, and thrust at four knots inflow velocity. It is not feasible to measure the inflow velocity into the propeller. Even a current estimate or measurement may be inaccurate in cases during which the propeller axis is not parallel with the current axis. As long as the inflow velocity cannot be introduced into the control algorithm, the system will experience errors. For instance, at 60% rpm, the system demands 36% thrust (the value for zero inflow), but it receives 22% thrust at four knots, an error of over 60%. A torque feedback (measuring the prime mover current) would have reduced the error to approximately 22%. From zero rpm up to approximately 80% rpm, controlling the power achieves the smallest error. With increasing rpm, this error grows larger until it reaches the same magnitude of the other control options, such as rpm or torque.

Conclusion: The graph indicates that, at higher inflow velocities, control of power leads to the closest relationship with thrust with the smallest error. However, from approximately 70% to 100% load on, this control also leads to increasing errors, which can only be corrected by introducing the inflow velocity into the algorithm.

Appendix:

Thruster Operation at Increased RPM: The typical thruster is designed for a certain rating regarding power, torque, thrust, rpm, etc. In order for the propeller to operate at full power during stationkeeping and during transit operations, the speed of the propeller must be increased to adapt to the higher inflow velocity. During constant power control operation, and with increasing inflow velocity (speed of the vessel), the torque in the drive system is reduced proportionally to the increase of the rpm and the propeller thrust is reduced due to the natural characteristic of the propeller. Typically, for most thruster designs, the shaft bearing loads are reduced and the calculated life of the bearings is increased under these conditions. Other factors which must be considered when operating at higher speeds include:

- The centrifugal forces acting on the propeller blades, which may cause an additional bending moment at the blade roots.
- The cavitation inception of the propeller during transit, in particular for the two aft propellers (lower submergence than the thrusters mounted under the bottom of the hull) due to the higher propeller rpm.
- The pitch line velocity of the right-angle gears, which should be within recommended limits.

[3] In Figures 5 and 6 the values for thrust, rpm, torque, and power were normalized by dividing these values by the design values. The design point for the propeller in this example is: power PD=4750 kW, torque Q=300.3 kNm, thrust T=877.47 kN, rpm=151, inflow velocity v=6.0 knots.

- The higher speed of the bevel wheel in the fully-flooded housing causes increased turbulence in the lubrication oil which results in increased heat in oil. This point was mentioned by a thruster manufacturer as one of the restricting factors. However, at increased inflow velocity, the water flowing over the outside of the gear housing is increased as well, improving the heat transfer from the lube oil through the steel housing into the sea water.

More Thrusters at Lighter Load for More Efficiency

There are several advantages in use of fixed pitch variable speed thrusters. One of the biggest is that they can be much more fuel-efficient when more thrusters are run at lower values of thrust. Our effort here is to quantify this improvement in efficiency. Fortunately, in most areas of the world, the weather will permit holding position at much less than full thrust for the vast majority of the time.

Modern power management systems support this well by allowing all thrusters to be running with only enough engines running to support the present load. This keeps the engine load up to a nice efficient level. It reduces engine wear and prevents smoking and slobbering, which are problems particularly with two stroke engines. It is not necessary to limit the number of thrusters in use to those that can be covered by the running engines. By the same token it is not necessary to run all of the engines that would be required if all of the thrusters suddenly need full thrust. In event of a sudden demand, the power management system will restrict thrust commands to prevent engine overload while additional engines are brought on line automatically.

Variable pitch full speed thrusters cannot enjoy this mode of operation. Several papers have documented the fact that full speed propellers consume roughly 30 percent of full power even at zero pitch while producing no thrust at all. Moreover, an extra engine is sometimes kept on line to permit starting the next big thruster motor if needed.

But how much improvement in efficiency is there in running fixed pitch thrusters at low thrust? First we will find the amount of improvement using some simple momentum equations. Then we will check the accuracy using Deter's real propeller data.

These equations are based on the fact that thrust is produced by the change in momentum as water is accelerated from a standing start, or still water, up to the velocity of the water as it passes through the nozzle of the thruster.

$$T = \rho A V^2$$

Equ 1

Here the thruster force is T, the mass density of water is ρ, and the cross sectional area and velocity of the "rod" of water going through the thruster are A, and V respectively.

Power is force time velocity, so you would think that the power consumed by the thruster would be found by multiplying the thruster force by the velocity of the water through the thruster. However, according to Deter's real propeller data it takes only two thirds that much power. Without knowing the real reason for this yet, we will use the 2/3 as a "fudge factor". It makes the calculation of thrust, power and velocity very close to the real propeller values, and in the end it is not a factor in our quantifying the improvement in thrust per horsepower.

Then,

$$P = \frac{2TV}{3} = \frac{2\rho A V^3}{3}$$

Equ 2

Here, in English units, power would be in foot-pounds per second, and to get horsepower you would have to divide by 550 ft-lbs/sec/HP.

We are interested in how much thrust we get for each horsepower we put into the water. By combining equations 1 and 2 we can see that:

$$\frac{T}{P} = \frac{3}{2V}$$

Equ 3

The thrust to power ratio is then simply the reciprocal of the thruster velocity, as modified by our fudge factor. If you know the pounds per horsepower that the thruster delivers at full thrust you can then determine the full-thrust water velocity in feet per second from equation 3. A thruster rated at 30 pounds per horsepower has a velocity of 27.5 ft/sec, and at 25 pounds per horsepower the velocity would be 33 ft/sec. So the lower the velocity the higher the specific thrust. This already says there is an improvement in efficiency by running slower.

Let's run our change of momentum thruster at a fraction of full thrust, X, where $X=T/T_{max}$ to see what happens to the thrust per horsepower.

From equ 1 we know that:

$$V = \left(\frac{T}{\rho A}\right)^{0.5}$$

Or:

$$V = \left(\frac{XT_{max}}{\rho A}\right)^{0.5}$$

Substituting from equ 1

$$V = \left(\frac{X \rho A V_{max}^2}{\rho A} \right)^{0.5}$$

Or:

$$V = (X)^{0.5} \left(V_{max} \right)$$

Substituting in equ 3, then:

$$\frac{T}{P} = \frac{3}{2\left(X^{0.5}\right)\left(V_{max}\right)}$$

Equ 4

Since from equ 3, $T_{max}/P_{max}=3/2V_{max}$, then substituting for V_{max} in equ 4, the fudge factors cancel.

$$\frac{T}{P} = \frac{T_{max}}{P_{max}\left(X^{0.5}\right)}$$

Equ 5

This now says that the thrust per horsepower of a thruster is proportional to the reciprocal of the square root of the fraction of thrust being used. The multiplier of the rated full load thrust per horsepower, T_{max}/P_{max}, is just $1/(X)^{0.5}$. The plot of this multiplier is shown on the following Fig 7.

The advantage at lower thrust is substantial. At 40 percent of full thrust we see a 60 percent increase in efficiency. At 20 percent the advantage is more than double the rated full load thrust per horsepower. If you have eight thrusters and decide to run all of them instead of half of them, you will use 30 percent less power. To run half of them will consume 40 percent more power than running all.

How does this theory check with propellers in the real world? Quite well, actually. Ratios of thrust per horsepower taken from Dietmar Deter's tables or curves of power and thrust compare with values calculated from equation 5 with accuracy to the third place over a wide range of thrust. So we could have simply calculated the improved thrust per horsepower directly from the propeller data. But it is nice to have a simple equation that shows the improvement for all propellers.

Velocity was calculated from the propeller table at various thrust levels using equation 4. From these values of velocity, the volumetric efficiency of the propeller was calculated using the following equation 6.

$$V = \frac{NEP}{60}$$

Equ 6

Here N is the number of revolutions per minute of the thruster; E is the volumetric efficiency, a reflection of slip through the propeller; and P is the pitch of the propeller, or the advance per revolution. These showed that the volumetric efficiency remained surprisingly constant at 81 percent over a wide range of thrust.

The substantial increase in thruster efficiency shown here at lower thrust levels does not take into account the fact that the power to run the thruster auxiliaries is about the same at all levels of thrust. This is not likely to detract much from the advantage. There is another advantage in running all thrusters and that is that there is no lost time in getting them running if they should be needed in a hurry to fight a sudden squall.

It is good to run all of the thrusters at light load, but that is not a good way to run the engines in the power plant. On the contrary, the power plant should run with as few engines on line as possible and at as high a load as possible. This requires a power management system that is very well designed and thoroughly tested.

About the Well Designed Power Management System

The DP system can be counted on to limit thrust commands to avoid overloading the power plant under normal conditions. DP control receives a power available signal from the PMS, which it uses to limit loads through thruster commands until PMS can automatically start more engines. It takes about 30 seconds to start another engine and a little less than enough thrust for that long will not result in much loss of position.

A more difficult condition arises when a generator breaker opens, say to clear a fault, and dumps its load on the engine or engines remaining on line. In some cases the minimum number of engines on line is only two. That is enough to be redundant, and it may be enough to drive sufficient fault current to clear a fault. If there are only two engines on line, there is reluctance to load them to more than 50 percent, even though the engines perform better when more heavily loaded. Limiting to 50 percent would supposedly keep the remaining load on failure of one to no more than 100 percent. However this is not a very tight limit. It is maintained by automatically starting the next engine at that level. But thruster loads could increase to the fixed power limit at 100 percent on each of two generators before additional generators can come on line. This could leave a 200 percent load for the remaining engine.

It takes about 3 to 5 seconds for the sudden load of a breaker opening to be brought under control by thrust command reduction. With a significant overload, that is about the time that it might take to kill an engine. At best this leaves the load limit lower than desirable and the timing of thrust command reduction somewhat marginal.

The new variable frequency drives offer the ability to drop load much more quickly. Making such reductions momentarily though the PMS or directly by the variable frequency drive can give short term load relief, independent of the DP system, until the slower DP commands can assume effective control. This offers the prospect of running higher engine loads with more solid control over DP failure from blackout.

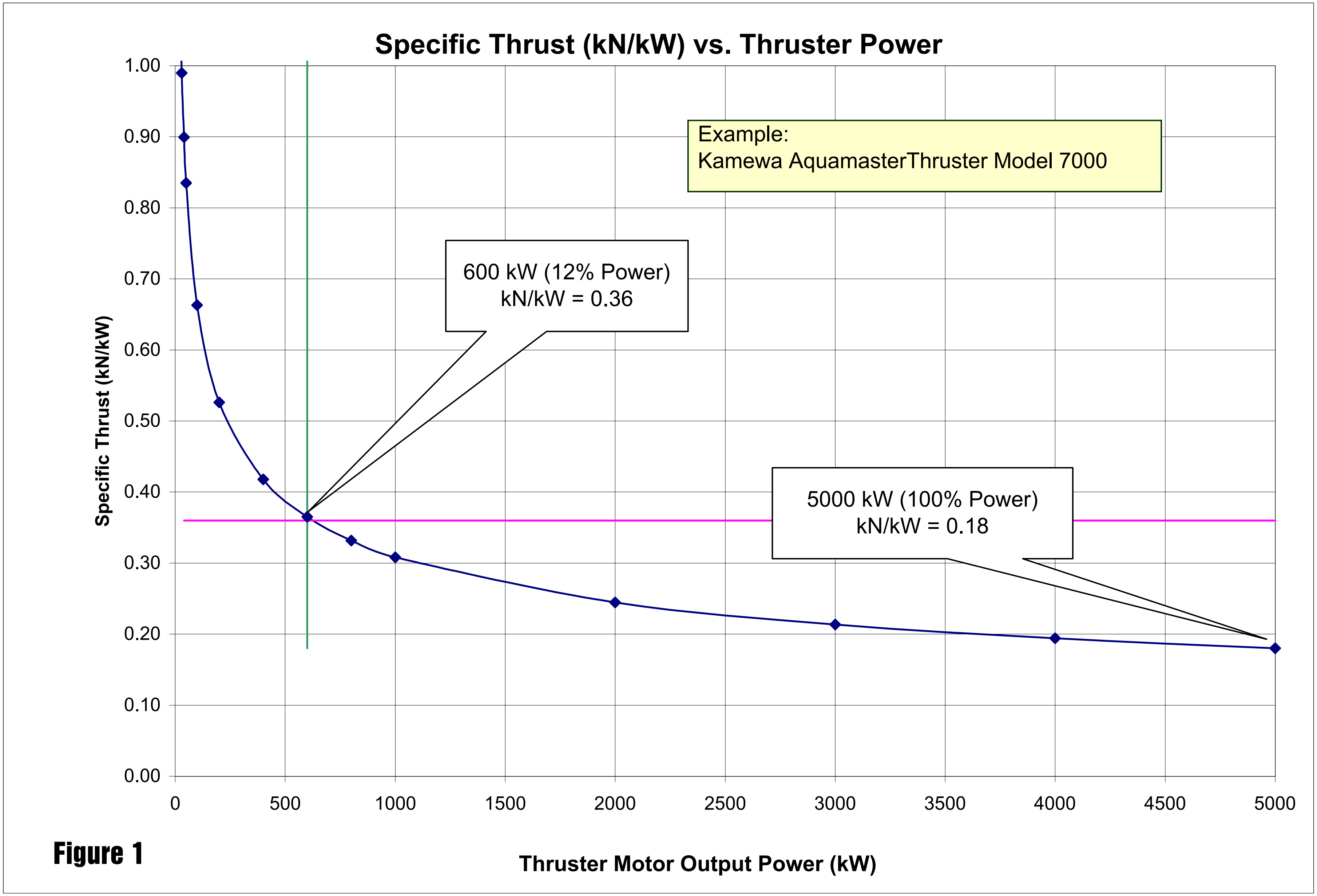
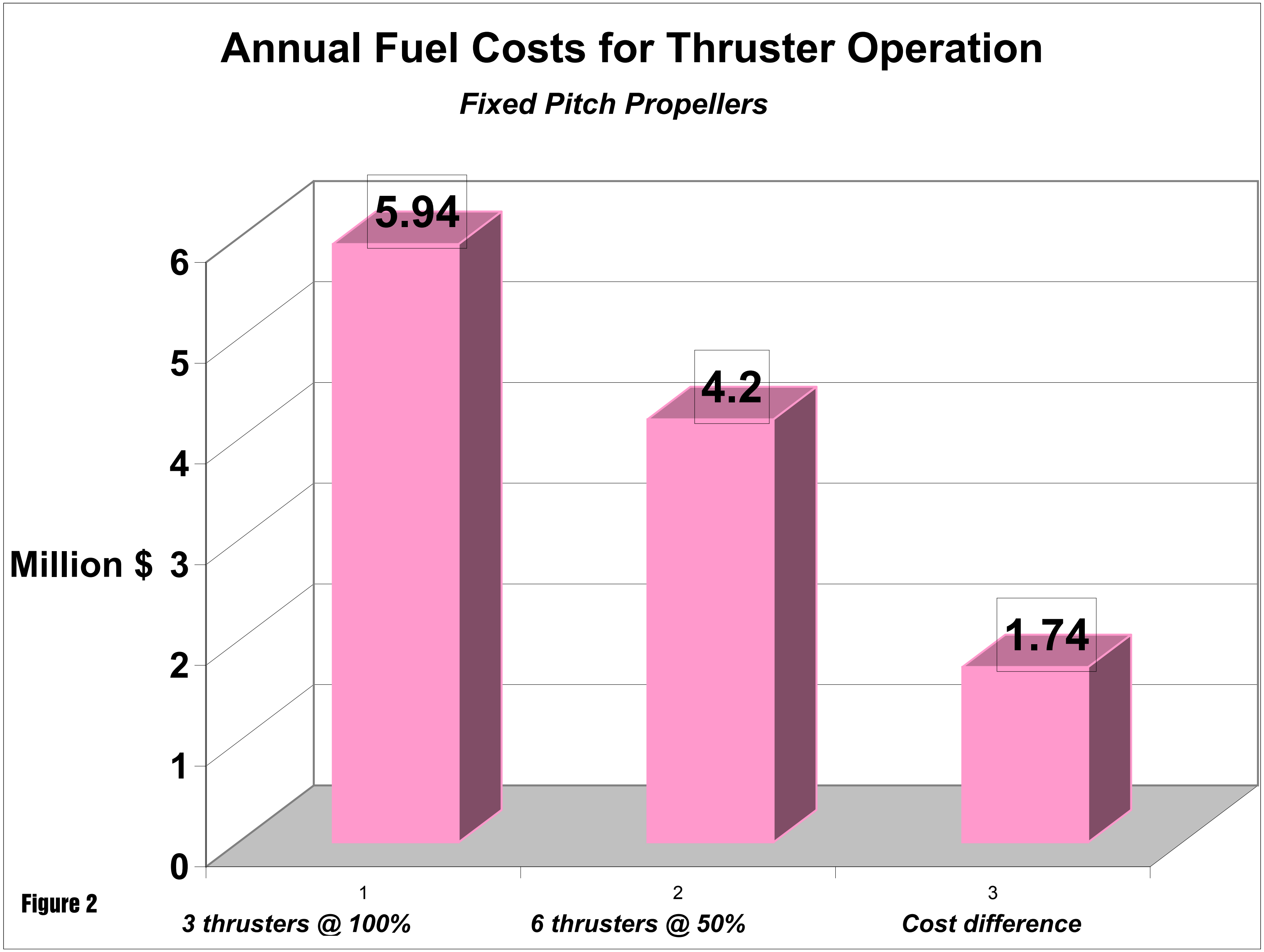

Specific Thrust (kN/kW) vs. Thruster Power
Specific Thrust (kN/kW)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
Example:
Kamewa AquamasterThruster Model 7000
600 kW (12% Power)
kN/kW = 0.36
5000 kW (100% Power)
kN/kW = 0.18
Thruster Motor Output Power (kW)

Figure 1


Annual Fuel Costs for Thruster Operation
Fixed Pitch Propellers
Million $
0
1
2
3
4
5
6
5.94
4.2
1.74
1
2
3
3 thrusters @ 100%
6 thrusters @ 50%
Cost difference
Figure 2

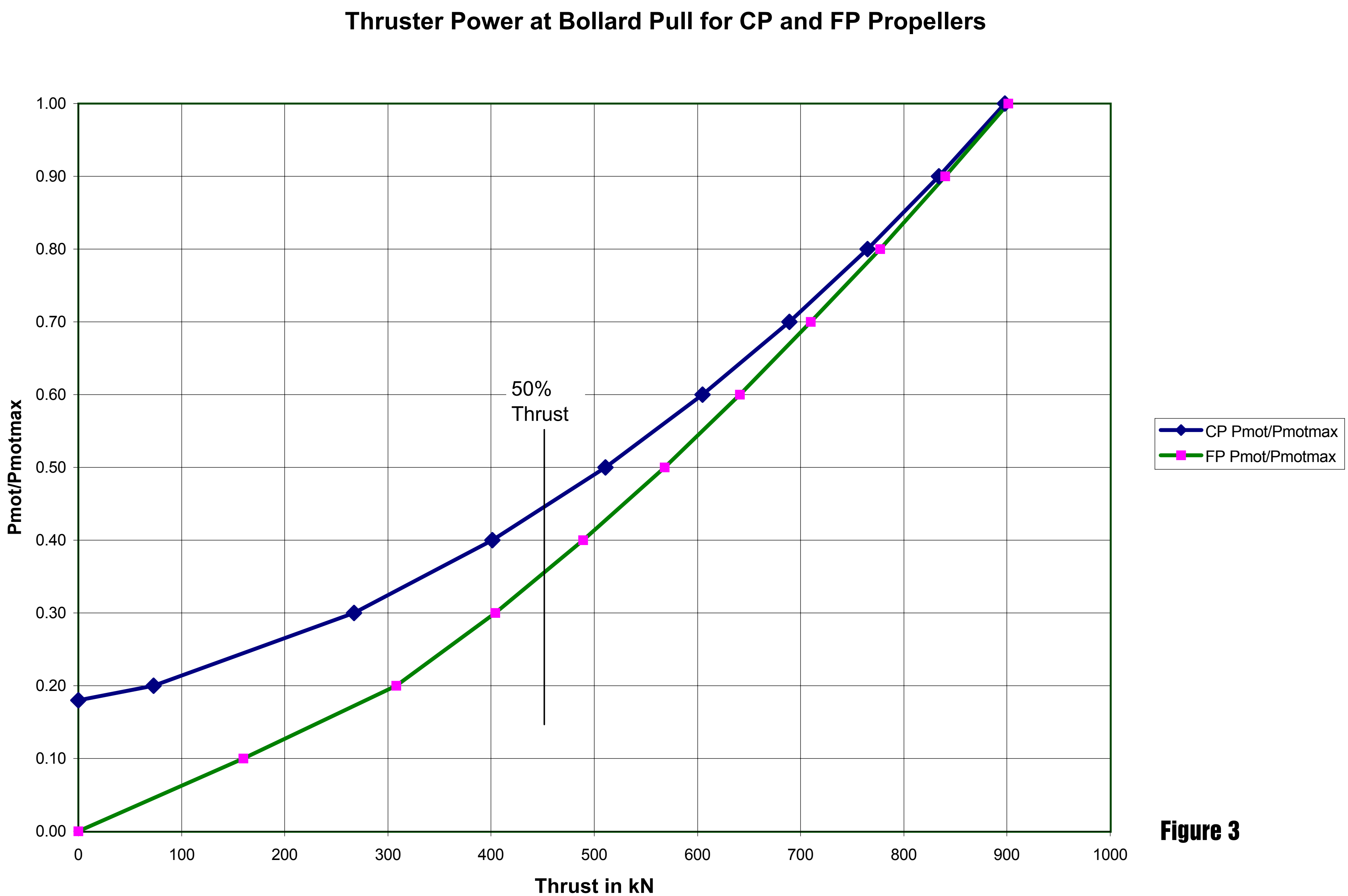
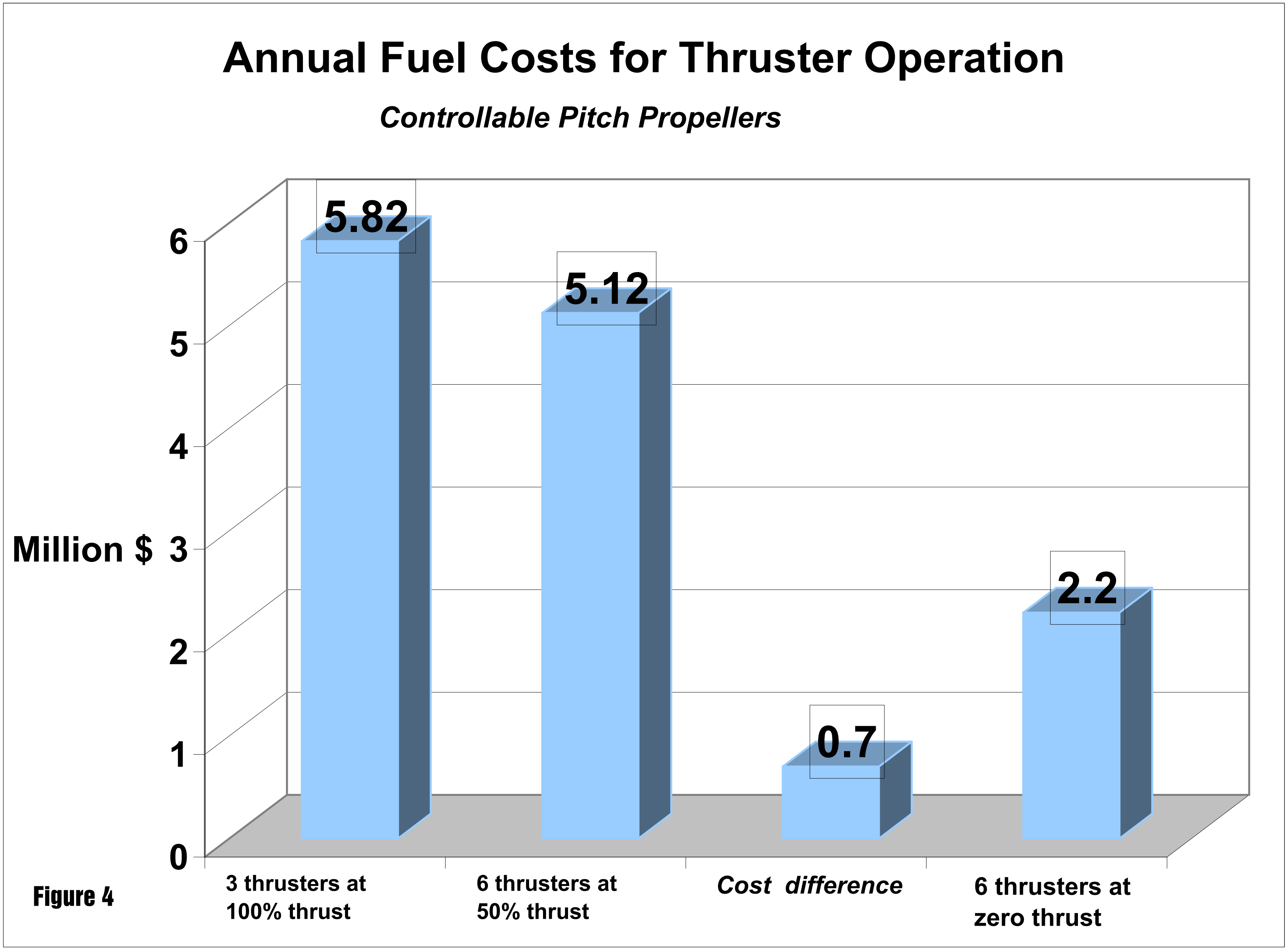

Thruster Power at Bollard Pull for CP and FP Propellers
Pmot/Pmotmax
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
0.10
0.00
0
100
200
300
400
500
600
700
800
900
1000
Thrust in kN
50%
Thrust
CP Pmot/Pmotmax
FP Pmot/Pmotmax

Figure 3


Annual Fuel Costs for Thruster Operation
Controllable Pitch Propellers
Million $
0
1
2
3
4
5
6
5.82
5.12
0.7
2.2
3 thrusters at 100% thrust
6 thrusters at 50% thrust
Cost difference
6 thrusters at zero thrust
Figure 4

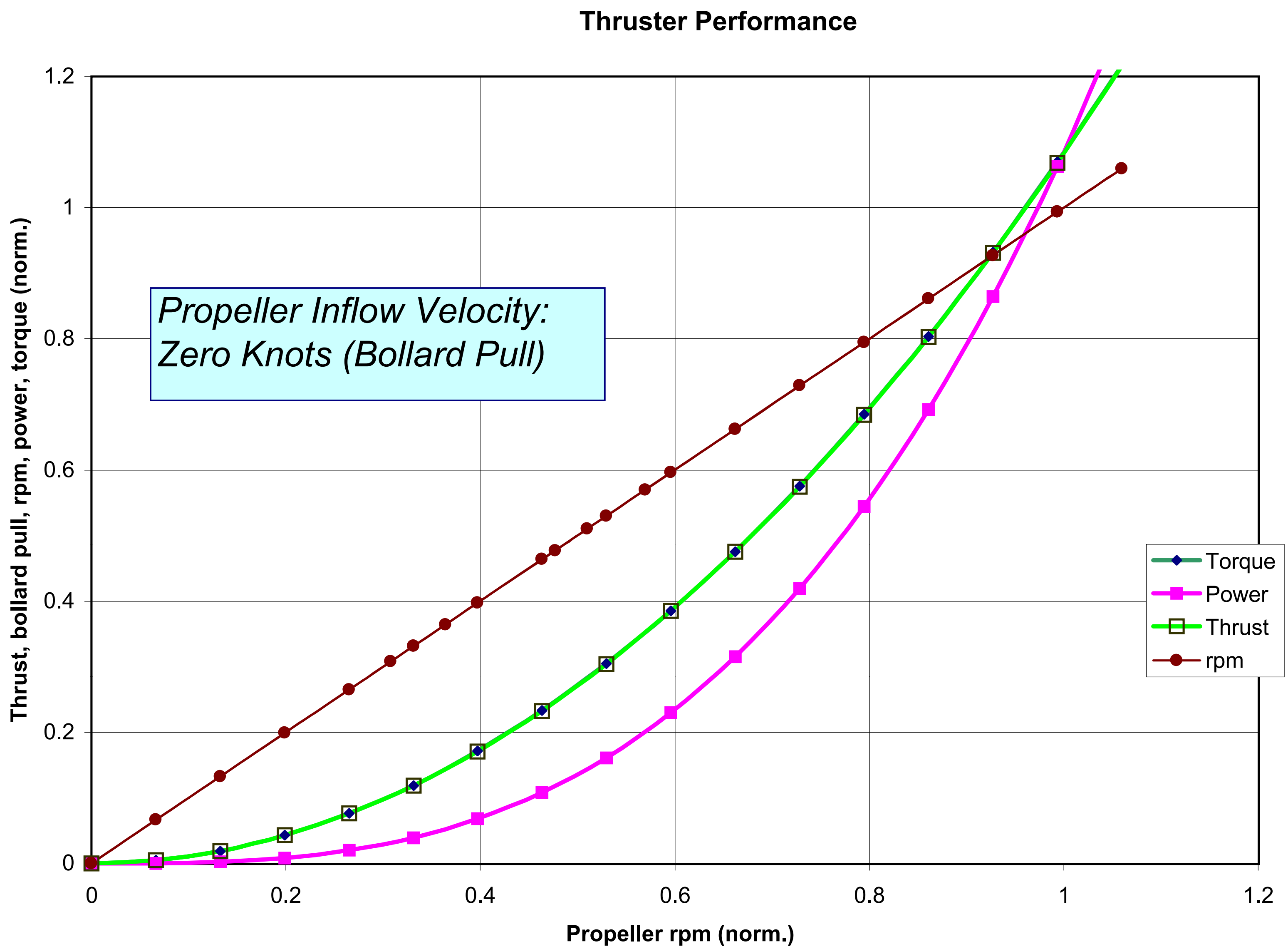
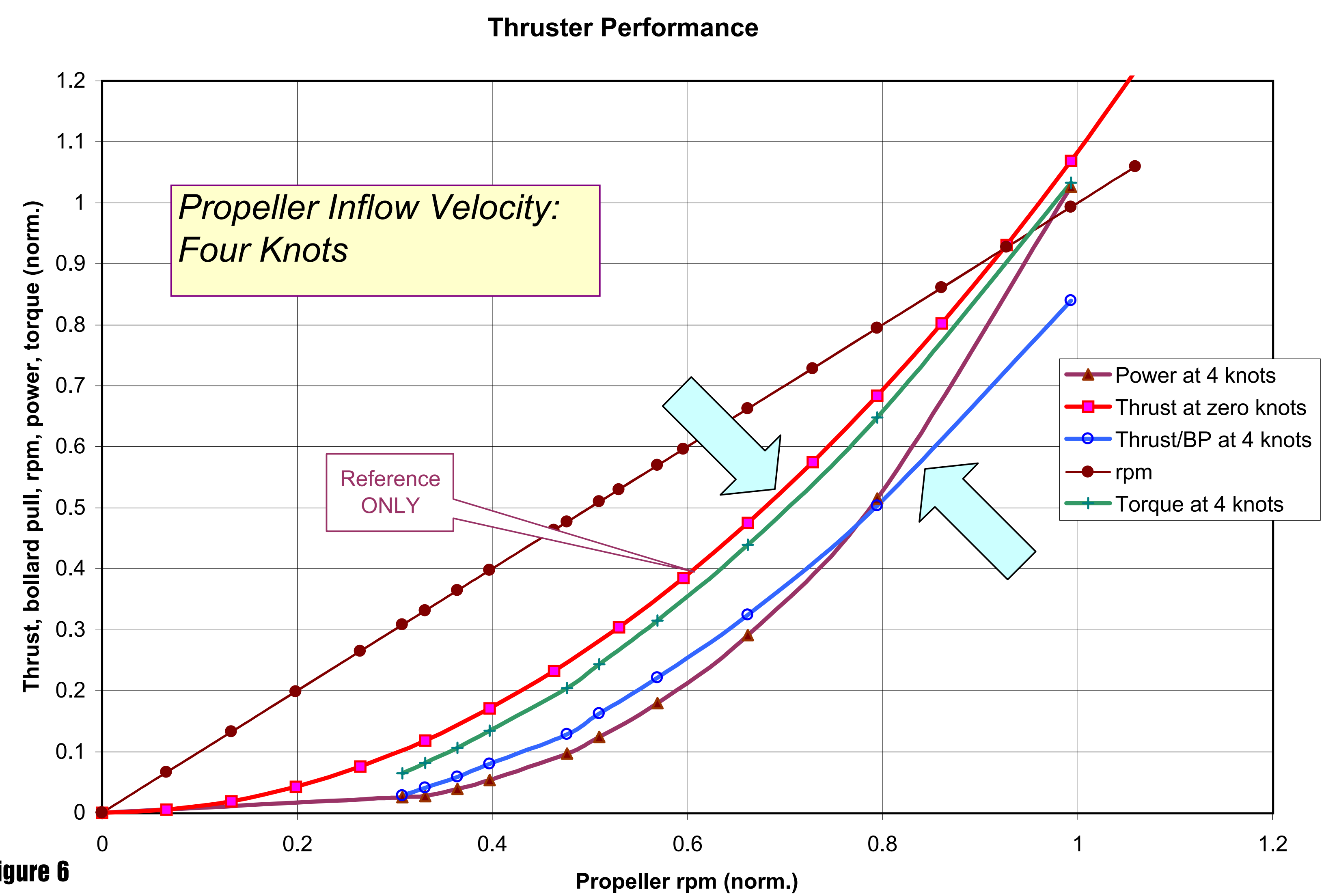

Thruster Performance
Propeller Inflow Velocity:
Zero Knots (Bollard Pull)
Torque
Power
Thrust
rpm
Thrust, bollard pull, rpm, power, torque (norm.)
Propeller rpm (norm.)
0
0.2
0.4
0.6
0.8
1
1.2

Figure 5



Thruster Performance
Propeller Inflow Velocity:
Four Knots
Reference
ONLY
Power at 4 knots
Thrust at zero knots
Thrust/BP at 4 knots
rpm
Torque at 4 knots
Thrust, bollard pull, rpm, power, torque (norm.)
Propeller rpm (norm.)
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2

Figure 6

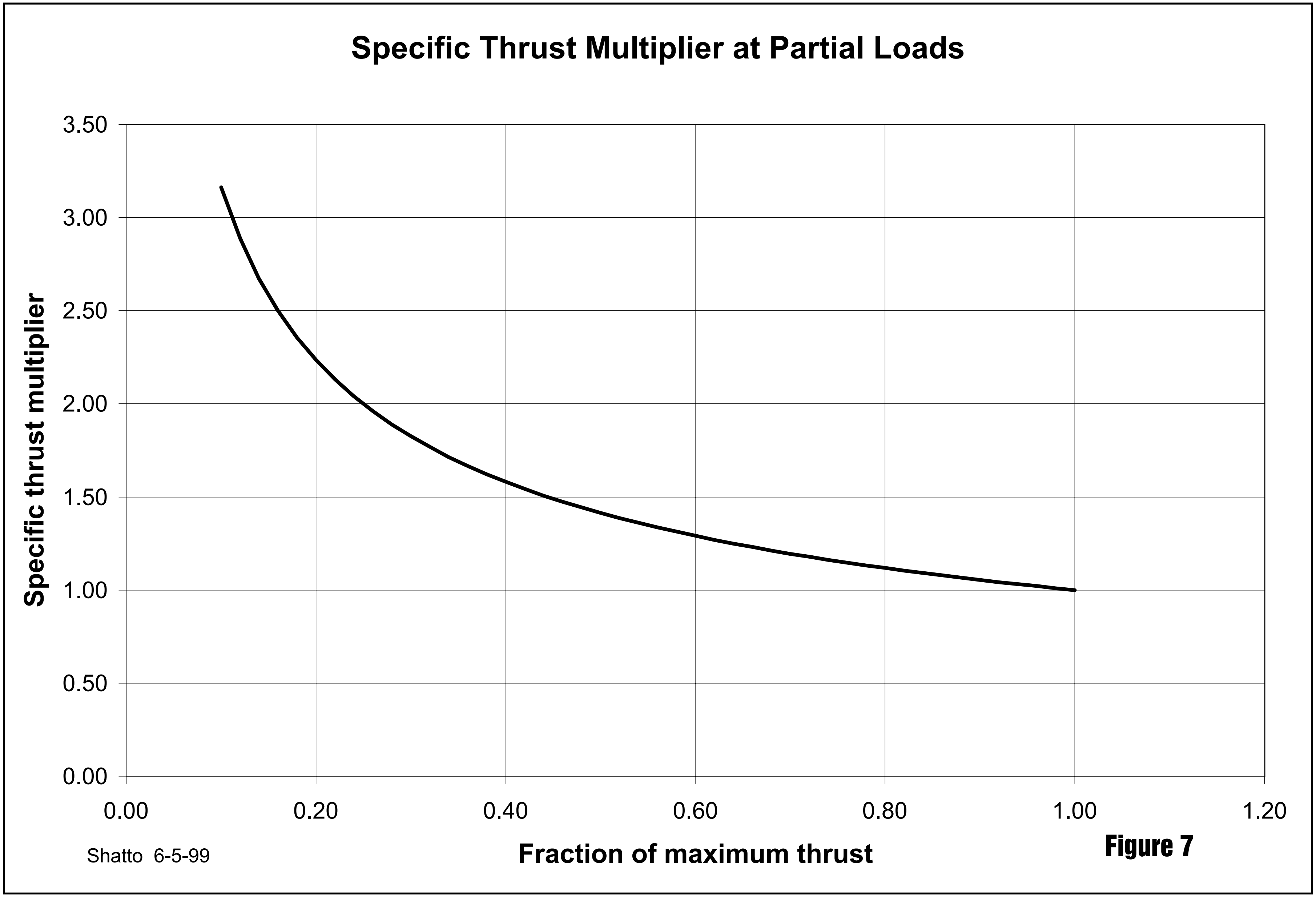

Specific Thrust Multiplier at Partial Loads
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
0.00
0.20
0.40
0.60
0.80
1.00
1.20
Specific thrust multiplier
Fraction of maximum thrust
Shatto 6-5-99

Figure 7