

An approach to transformation of non-dimensional diagrams into nomograms and its application to new propeller design system

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Abstract

This paper is concerned with the software for designing propellers. The nomograms are made of the non-dimensional charts which are results of a series of propeller tests and generally used by the designers. The system brings designers in remarkable convenience keeping reasonable accuracy.

1 Introduction

The nomogram system consists of a base scale and a set of overlays.

The discussion in detail will be done on the horsepower system mainly.

An example of propeller design will be shown.

2 Theory of base scale

2.1 Forming base scale

The equation to form a base scale is as follows:

$$X \cdot [\text{length}] + Y \cdot [\text{velocity}] = \log (A / A_0) \quad (1)$$

[] means dimension, A the parameter having the same dimension as the dynamics value and A₀ the constant having the same dimension as A. Several kinds of dimensions about dynamics together with A₀ are shown in table 1. Especially a set of length, velocity and density has been taken as the base unit.



Table 1: Dimensions and A0

	[LENGTH]	[VELOCITY]	[DENSITY]	A0
LENGTH	1	0	0	1m
VELOCITY	0	1	0	10kt
HORSE POWER	2	3	1	100PS
ANGULAR VELOCITY	-1	1	0	1000rpm
TIME	1	-1	0	10s
FORCE (WEIGHT)	2	2	1	1.457t
MOMENT OF FORCE (TORQUE)	3	2	1	71.619kg*m
AREA	2	0	0	10m ²
STRESS (ELASTIC COEFFICIENT)	0	2	1	1000kg/mm ²
ACCELERATION	-1	2	0	10m/s ²
PRESSURE	0	2	1	1kg/cm ²
SURFACE TENSION	1	2	1	1g/cm
KINEMATIC VISCOSITY	1	1	0	1mm ² /s
COMPRESSIBILITY	0	-2	-1	1mm ² /t
DENSITY	0	0	1	100kg*s ² /m ⁴

Figure 1: .1m and 1m

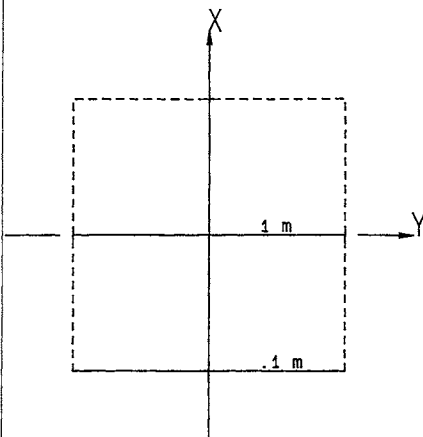


Table 2: Example data

	(A)	(B)
L (1) (m)	.1663	.71
L (2) (m)	1.171	5
V (1) (kt)	25.97	75
V (2) (kt)	4.848	14
P (PS)	6.379	2800
N (rpm)	2291	1550
t (s)	20.3	30
F (t)	.00461	.7
M (kg*m)	3083	200
rho (kg*s ² /m ⁴)	104.5	104.5
-	-	-
-	-	-

A base scale is made from eqn (1) and table 1. X is taken for ordinate, Y for abscissa. As an example, taking "length" as one of the dynamics value, eqn (1) will be $X \cdot 1 + Y \cdot 0 = \log (A/1m)$. In the case of $A=.1m$, this equation will be $X \cdot 1 + Y \cdot 0 = \log (.1m/1m)$, showing the ".1m" line in figure 1. Especially if $A=A_0$, this equation makes $X \cdot 1 + Y \cdot 0 = 0$, showing the line having the origin. The base scales having several kinds of dynamics values are shown in figure 2, which are arranged in parallel to be easy to see.

2.2 Base scale's quality

As one of the example, we select the case as follows: $L(1)=.1663m$, $L(2)=1.171m$, $V(1)=25.97kt$, etc. in (A) column of table 2 are obtained by experiment etc. If we plot these data on the base scale, the circle marks are got as figure 3. The parallel translation as the double circle marks bring us in the data on (B) column $L(1)=.71$, $L(2)=5m$, $V(1)=75kt$ etc. under constant ρ value.

As one of the examples non-dimensional value $M / (\rho \cdot N^2 \cdot L(1)^5)$ can be formed by $L(1)$, $L(2)$, $V(1)$, etc. The value is the same for both cases of (A) and (B) columns.

3 Horsepower system's base scale

A horsepower system's base scale that is used for the propeller calculation under horsepower system is obtained by selecting four base scales LENGTH, VELOCITY, HORSEPOWER and ANGULAR VELOCITY from figure 2's ones to superpose one another. (See figure 4).

4 Overlay

The most recommendable overlay among several overlays is the "Form "[Pd - N] : (Va - D), p, Vac' : (Va - Pt), p overlay", which will be discussed.

The second row of table 3 consists of p, Ep, J, Kq, ρ , Pd, N, D, Va, Pt, Vac' and Vas. A set of p, Ep, J and Kq is read by the chart for B..A.R.=.5 of Gawn type propellers in reference [1]. ρ , Pd and N are set as $104.5kg \cdot s^2/m^4$, 100PS and 1000rpm respectively. D, Va and Pt are also obtained by using p, Ep, J, Kq, P, Pd and N. Double circle mark show us the intersection of each (Va - Ep) curve and the (Va - Ep) curves' envelope curve.

We will discuss Vac' and Vas.

4.1 Vac'

We suppose a propeller keeps constant J value and runs under water pressure. To keep J being constant value, not only Va but also N is necessary to increase both values under the relation of $N=Va / (D \cdot J)$. Increasing Va value together with N one causes water pressure to decrease until the equal pressure level between water's vapour pressure and propeller blade's water pressure at a point, which is beginning of cavitation. We define Va and N at the beginning of

Figure 2: Base scales

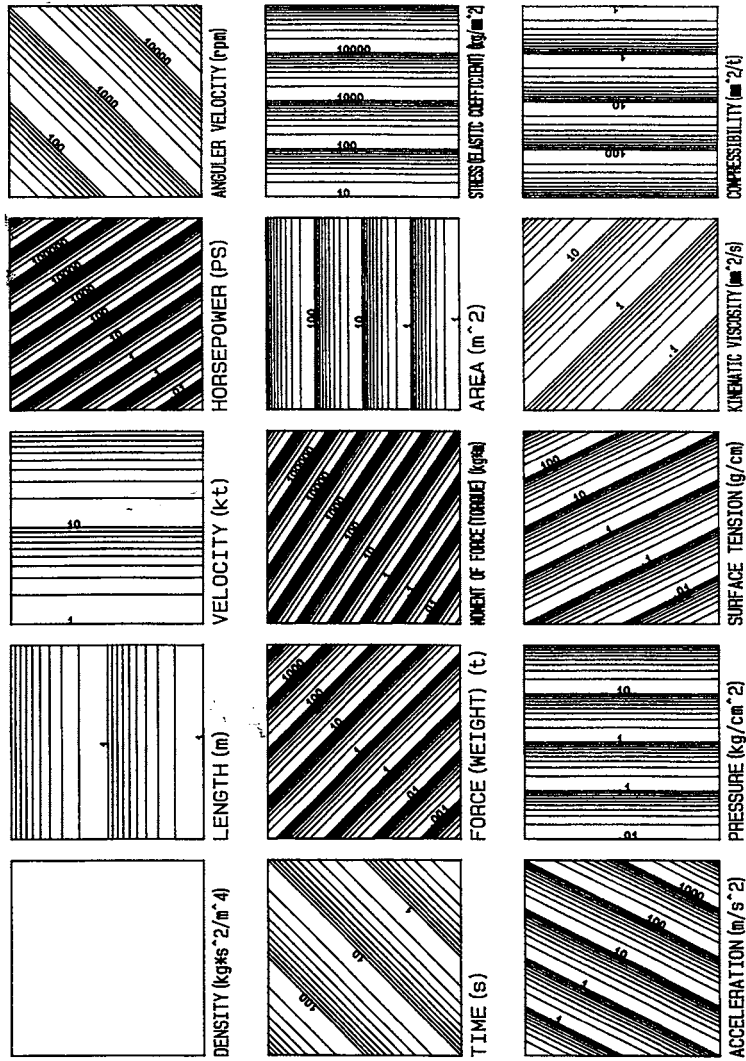


Figure 3: Parallel translation

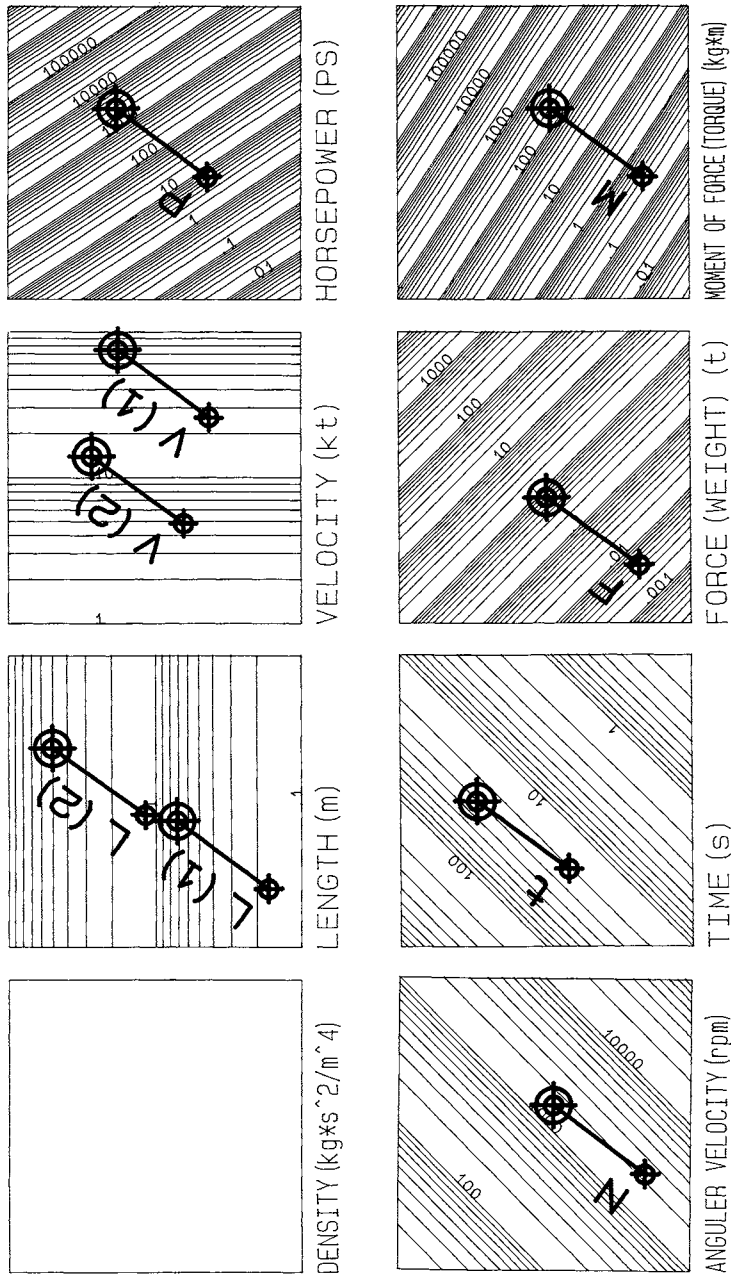


Table 3: Gawn's propeller test data

B.A.R.=.5 ; Z=3 ; X1=.2 ; c=.0113/.74 ; p0.9R=p											
p	Ep	J	Kq	rho (#)	Pd (PS)	N (rpm)	D (m)	Va (kt)	Pt (PS)	Vac' (kt)	Vas (kt)
2	.6	2.03	.0265	104.5	100	1000	.622	40.9	60	94.83	82.27
2	.8	1.815	.0484	104.5	100	1000	.5514	32.42	80	49.02	49.93
2 	.8125	1.713	.0582	104.5	100	1000	.5314	29.49	81.25	40.43	42.24
2	.8	1.597	.069	104.5	100	1000	.5136	26.57	80	33.51	35.7
2	.6	1.08	.1175	104.5	100	1000	.4617	16.15	60	16.42	18.02
2	.4	.705	.1512	104.5	100	1000	.439	10.02	40	9.28	10.3
2	.2	.35	.18	104.5	100	1000	.424	4.8	20	4.14	4.67
1.8	.6	1.835	.0218	104.5	100	1000	.6467	38.45	60	91.27	82.22
1.8	.8	1.613	.0434	104.5	100	1000	.5635	29.45	80	43.91	45.86
-	-	-	-	-	-	-	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-

#: kg*s²/m⁴

Figure 4: Horsepower system's base scale

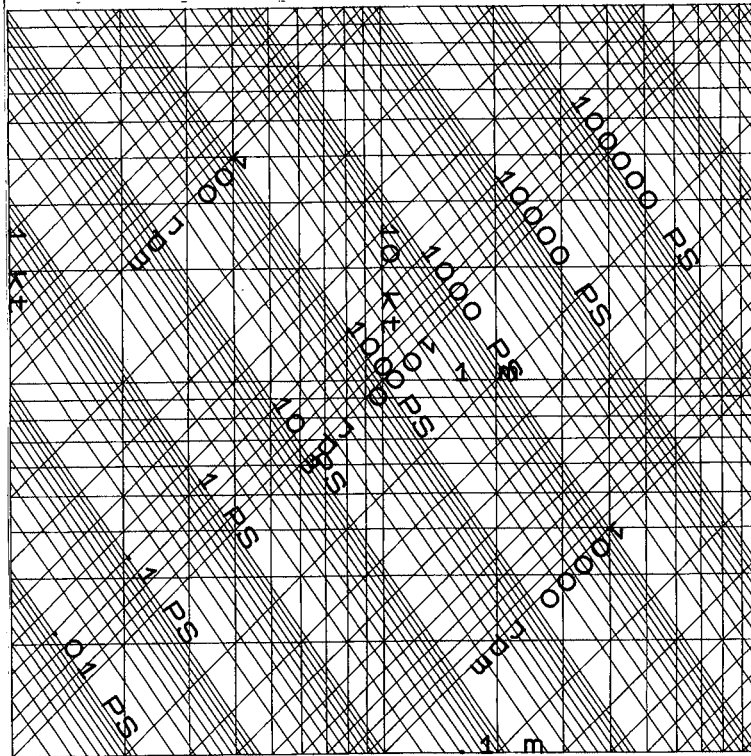
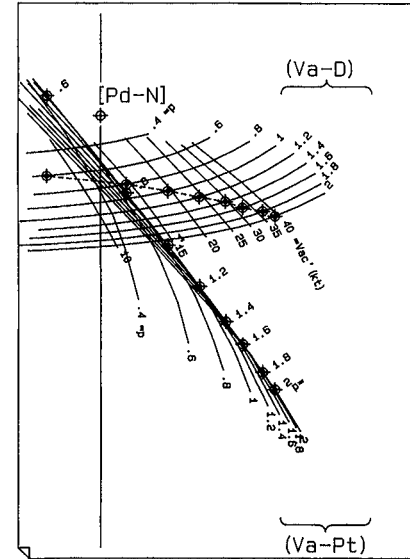


Figure 5: Contours $(V_a - D)$, p and $(V_a - D)$, V_{ac} ; $(V_a - P_t)$, p



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cavitation as V_{ac} and N_c respectively. If the scale-effect items such as Froude number, Reynolds number and Weber number can be ignored, V_{ac} has no relation with a propeller's dimension. (See VELOCITY and PRESSURE base scale in figure 2)

Eggert obtained N_c on the supposition that the blade back's cavitation begins on the arc of $0.9R$ [2],[5]. R means propeller's radius.

$$N_c \text{ (rps)} = .635 / D(m) \cdot (H(m) \cdot (1+4 \cdot bmn) / ((\alpha+c) \cdot k))^{1/2} \quad (2)$$

If we multiply eqn (2)'s each side by J ($=V_{ac} / (N_c \cdot D)$), the equation is transformed into

$$V_{ac} \text{ (kt)} = (H(m))^{1/2} \cdot 3600 \cdot .635 / 1852 \cdot ((1+4 \cdot bmn) / ((\alpha+c) \cdot k))^{1/2}$$

We define V_{ac}' as the case of $I=0m$ and $H=10.34m$ in the equation or the case of equality in pressure level between the water pressure and atmosphere one. Then

$$V_{ac}' \text{ (kt)} = 10.34^{1/2} \cdot J \cdot 3600 \cdot .635 / 1852 \cdot ((1+4 \cdot bmn) / ((\alpha+c) \cdot k))^{1/2} \quad (3)$$

$$V_{ac} \text{ (kt)} = V_{ac}' \text{ (kt)} \cdot (1+I(m)/10.34)^{1/2} \quad (4)$$

We set $I=D$ from now on.

4.2 V_{as}

As the case of V_{ac} we suppose a propeller keeps its scale and constant J value. But the propeller has enough water pressure not to occur cavitation. Increasing V_a value as the case of V_{ac} causes compressive stress at a point P_1 on the propeller's blade root to increase up to allowable compressive stress. We define V_a at the allowable compressive stress as V_{as} .

V_{as} has no relation with propeller's dimension under the condition that scale-effect is negligible small. (See base scales VELOCITY and STRESS (ELASTIC COEFFICIENT) in figure 2)

$$V_{as} = (S_0 \cdot V_a^2 / SCC)^{1/2} \quad (5)$$

We take $S_0=800g/mm^2$. The following equations are derived from reference [2].

$$SCC = SC + SIG_c - SIG_1 \quad (6)$$

In the case of Gawn type propellers, the relation $V_{ac}' < V_{as}$ is kept except the special case. Then we omit V_{as} from the calculation hereafter.

5 Making of “Form [Pd - N] : (Va - D), p, Vac’: (Va - Pt), p overlay”

Table 3 is used to make the overlay.

First of all, an overlay should be fixed on the base scale.

The first row of the table 3 reads $p=2$, $Pd=100PS$, $N=1000rpm$, $D=.622m$, $Va=40.9kt$, $Pt=60PS$ and $Vac'=94.83kt$.

Then successive plots are done as follows:

- (1) The intersection of lines 100PS and 1000rpm is plotted, which is written as the [Pd - N] point.
- (2) The intersection of lines 40.9kt and .622m is plotted, which is written as the (Va - D) point. Also we should note down the items $p=2$ and $Vac'=94.83kt$.
- (3) The intersection of lines 40.9kt and 60PS is plotted, which is written as the (Va - Pt) point. Also we should note down the item $p=2$.

Repeating similar work as these one about all rows of table 3, we got a point [Pd - N] superposed together with many (Va - D) and (Va - Pt) points. The noting down items p and Vac' for the (Va - D) points and p for the (Va - Pt) points are still written. The point that is written by double circle mark in table 3 should be expressed by double circle mark.

p 's contours and Vac' 's contours are made of many (Va - D) points. The former is called as (Va - D), p contours and the latter (Va - D), Vac' contours. Also p 's contours are made of many (Va - Pt) points, which will be called as (Va - Pt), p contours hereafter. (See figure 5) Each point that is marked by double circle mark among (Va - D) points is linked to form the (Va - D) envelope curve. Similarly each point that is marked by double circle mark among (Va - Pt) points is linked to form the (Va - Pt) envelope curve. p value should be written on the (Va - Pt) envelope curve.

- a. We regard the [Pd - N] point as “design point 1”, by which Pd and N are read.
- b. We regard a point plotted on the (Va - D) region as “design point 2”, by which Va, D, p and Vac' are read.
- c. We regard a point plotted on the (Va - Pt) region as “design point 3”, by which Va, Pt and p are read.

It is necessary that Va value got by design point 2 have the same value as Va one got by design point 3. Also p value requires the similar plotting.

6 Design work of A-boat's propeller

The conditions of the design are as follows:

- (1) $Pd=685PS$ and $N=2120rpm$.
- (2) (Va - Pt) curve is set on ship side.

Va (kt)	22.00	26.42	30.83	36.00
Pt (ps)	263.0	383.4	548.2	830.0

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First of all, $(V_a - P_t)$ curve is written on base scale. The intersection of lines 685PS and 2120rpm on base scale is superposed by the $[P_d - N]$ point on the overlay for B.A.R.=5.

$p=.6$ is set tentatively. The design point 3 is the intersection of lines .6 curve among the $(V_a - P_t)$, p contours and $(V_a - P_t)$ curve, which shows us $V_a=25.8\text{kt}$ and $P_t=365\text{PS}$. Successively the design point 2 is got, which shows us $D=.695\text{m}$ and $V_{ac}'=19.2\text{kt}$.

As a special case, we search p having maximum V_a . The design point 3 is taken by the intersection of the $(V_a - P_t)$ curve and the $(V_a - P_t)$ envelope curve. By this point we got the items $p=.95$, $V_a=28.5\text{kt}$ and $P_t=455\text{PS}$. Successively the design point 2 is determined as the previous case, we can also read items $D=.588\text{m}$ and $V_{ac}'=18\text{kt}$. (See figure 6)

We should notice that A-boat's propeller does not satisfy the design condition under $V_a < V_{ac}'$. In such a case, bringing new overlay having larger value in B.A.R. to us, we should continue the similar calculations. Even the overlay having 1.1 in B.A.R. could not obtain the propeller satisfying A-boat's design conditions.

Decreasing N is necessary. The case of slowdown at $N=1750\text{rpm}$ was discussed. As a result, we managed to obtain the propeller satisfying the condition $V_a < V_{ac}$. But this propeller does not satisfy the condition $V_a < V_{ac}'$. (See table 4)

7 Art of reading Ep

Without the art we cannot read Ep on "Form $[P_d - N] : (V_a - D)$, p , $V_{ac}' : (V_a - P_t)$, p overlay". The simple art to read Ep is as follows: The overlay's $[P_d - N]$ point is superposed and fixed on base scale's 100PS line. Onto the overlay we copy base scale's lines 100PS, 90PS, etc. and define the Ep values $Ep=1.0$, .9 etc. respectively. Then we can read Ep on design point 3.

8 Thrust and torque system's base scale

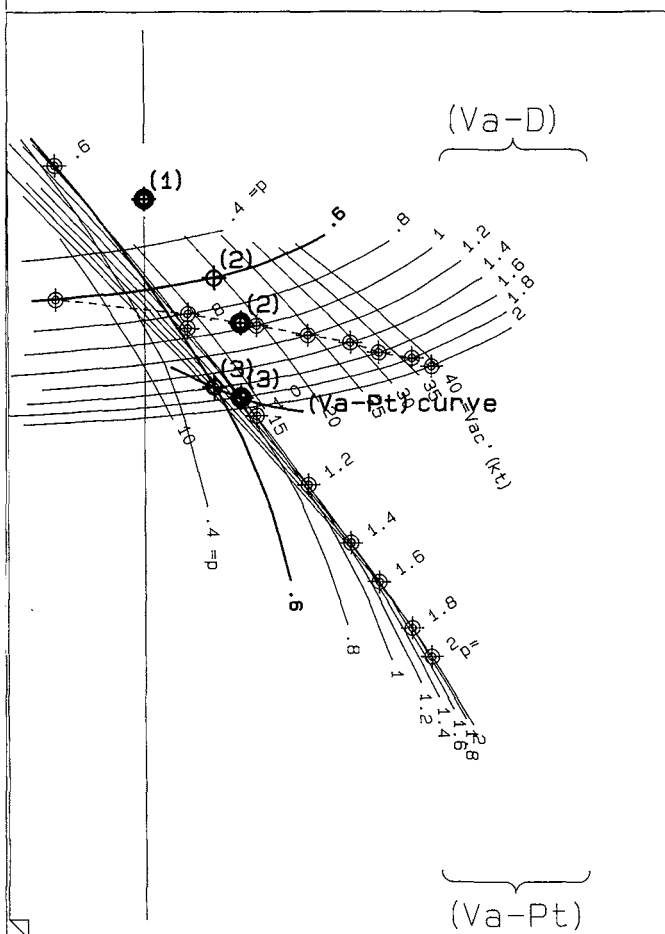
A thrust and torque system's base scale is got by selecting five base scales among the figure 2's ones LENGTH, VELOCITY, FORCE (WEIGHT), MOMENT OF FORCE (TORQUE) and ANGULAR VELOCITY to superpose onto one of them, which enables us to calculate propellers the way thrust and torque system works.

Putting thrust torque base scale in place of horsepower base scale, we can read Q and N at the design point 1 and V_a and T at the design point 3. Both substituting $(V_a - T)$ curve for $(V_a - P_t)$ curve and substituting $(V_s - R)$ curve for $(V_s - P_e)$ curve have been done. Where $Q=P_d / (2 \cdot \pi \cdot N)$, $T=P_t / V_a$ and $R=P_e / V_s$.

Table 4: V_a and V_{ac}' at $N=2120$ and 1750rpm

B.A.R.	Pd (PS)	N (rpm)	p	D (m)	Pt (PS)	V_a (kt)	V_{ac}' (kt)	
.5	685	2120	.6	.695	365	25.8	19.2	$V_a > V_{ac}'$
.5	685	2120	.95	.588	455	28.5	18	$V_a > V_{ac}'$
.8	685	2120	1.005	.567	444	28.25	21	$V_a > V_{ac}'$
1.1	685	2120	1.02	.542	415	27.4	24.2	$V_a > V_{ac}'$
1.1	685	1750	1.09	.605	431	27.9	27.3	$V_a > V_{ac}'$

Figure 6: Design points (1);(2) and (3)



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10 Nomenclature

“ $\cdot$ ” or “ $*$ ”, “/”, “ $^{\wedge}$ ” and “kg or t” : product, division, power and kilogram or ton force.

bmn : $\pi \cdot B \cdot A \cdot R \cdot / (2 \cdot Z \cdot (1 - X_1))$.

c : cross section's ratio of thickness to width at 0.9R in case of arch cross section.

H : 10.34m + I.

I : depth from water line to center of propeller axis.

k : $1 + (p0.9R \cdot (1 - s/2)/\pi)^2$.

Nc : propeller's speed of revolution at cavitation beginning.

p0.9R : 0.9R cross section's pitch ratio.

S0 : allowable compressive stress.

SC : compressive stress at the point P_1 due to thrust and torque.

SCC : compressive stress at the point P_1 on blade root.

S1G1 : tensile stress at the blade root due to centrifugal force.

S1Gc : compressive stress at the point P_1 due to centrifugal force in case of blade having rake.

s : $1 - J/p$.

X1 : boss ratio.

α : $p0.9R \cdot s \cdot (2 - s) / (2 \cdot \pi \cdot (2 \cdot k - s))$.

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