SSME SEAL TEST PROGRAM: TEST RESULTS FOR SAWTOOTH PATTERN DAMPER SEAL--INTERIM PROGRESS REPORT

NASA CONTRACT NAS8- 35824

Prepared by

Dara W. Childs, Ph.D., P.E.

Professor of Mechanical Engineering

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TRC-Seal-1-86

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ABSTRACT

Test results consisting of direct and transverse force coefficients are presented for eleven, sawtooth-pattern, damper-seal configurations. The designation "damper" seal refers to a seal which uses a deliberately roughened stator and smooth rotor as suggested by von Pragenau [1] to increase the net damping force developed by a seal. The designation "sawtooth-pattern" refers to a stator roughness pattern whose normal cross section to the axis of the seal resembles a saw tooth with the teeth direction opposing fluid motion in the direction of shaft rotation. The sawtooth pattern yields axial grooves in the stator which are interrupted by spacer elements which act as flow constrictions or "dams".

All seals tested use the same smooth rotor and have the same, constant, minimum clearance. The stators which were tested examined the consequences of changes in the following design parameters:

(a) axial-groove depth (tooth height),

(b) number of teeth,

(c) number of sawtooth sections,

(d) number of spacer elements (dams),

(e) dam width,

(f) Axially aligned sawtooth sections versus axially-staggered sawtooth sections, and

(g) Groove geometry.

From a rotordynamics viewpoint, none of the sawtooth-pattern seals performs as well as the best round-hole-pattern seal. The best sawtooth-pattern stator yielded 18% more net damping than a smooth seal

versus 38% more net damping for the best round-hole-pattern damper seal. Maximum damping configurations for the sawtooth and round-hole-pattern stators had comparable stiffness performance; however, the maximum-damping saw-tooth-pattern stator leaked approximately 20% more than the maximum-damping round-hole pattern stator.

From a leakage viewpoint, several of the sawtooth pattern stators outperformed the best (maximum-damping) round-hole pattern seal by approximately 20%.

LIST OF FIGURES

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NOMENCLATURE

c: Cross-coupled damping coefficient, introduced in Eq. (1), FT/L.

k: Cross-coupled stiffness coefficient, introduced in Eq. (1), F/L.

mr, nr: Empirical turbulence coefficients to define the seal-rotor friction factor.

ms, ns: Empirical turbulence coefficients to define the seal-stator friction factor.

A: Dynamic seal eccentricity, introduced in Eq. (2).

C: Direct damping coefficient, introduced in Eq. (1), FT/L.

C_{ef}: Net damping coefficient, introduced in Eq. (10), FT/L.

C_D: Discharge coefficient, introduced in Eq. (11).

C_L: Leakage coefficient, introduced in Eq. (12).

C_r: Minimum radial seal clearance, L.

F_X, F_Y: Cartesian components of the seal reaction force, introduced in Eq. (1), F.

F_r, F_θ: Radial and circumferential components of the seal reaction force, F.

K: Direct seal stiffness coefficient, introduced in Eq. (1), F/L.

M: Seal added mass coefficient, introduced in Eq. (1), M.

M_{ef}: Effective seal added-mass coefficient, introduced in Eq. (10), M.

ΔP: Seal pressure differential, F/L^2.

R: Seal radius, L.

$R_a = 2\rho V C_r/\mu$: Reynolds number.

V: Average axial fluid velocity in the seal L/T.

X, Y: Seal displacement components, introduced in Eq. (1), L.

λ_r: Seal rotor friction factor, defined in Eq. (5).

$\sigma = \lambda(L/C_r)$: Axial pressure-gradient coefficient.

ρ: Seal density, M/L^3.

ω: Seal rotational and precessional velocity, T^{-1}.

μ: Seal viscosity, FT/L^2.

INTRODUCTION

The test and analysis results which are reported here were obtained under NASA Contract NAS8-35824. The present work continues research activity which began in January of 1980 under NASA Contract NAS8-33716. Earlier contract reports [3-7] provide detailed information covering the following points:

(a) test-section and facility description,

(b) test-objectives and procedures, and

(c) data acquisition, analysis and procedures.

Most of this information is not repeated here, and interested readers are referred to earlier reports.

From a rotordynamics viewpoint, seal analysis has the objective of predicting the coefficients for the following motion/reaction-force model

$$-\begin{Bmatrix} F_X \\ F_Y \end{Bmatrix} = \begin{bmatrix} K & k \\ -k & K \end{bmatrix} \begin{Bmatrix} X \\ Y \end{Bmatrix} + \begin{bmatrix} C & c \\ -c & C \end{bmatrix} \begin{Bmatrix} \dot{X} \\ \dot{Y} \end{Bmatrix} + M \begin{Bmatrix} \ddot{X} \\ \ddot{Y} \end{Bmatrix} , \qquad (1)$$

where X, Y are components of the seal-rotor displacement relative to its stator and F_X, F_Y are components of the reaction force. The diagonal and off-diagonal stiffness and damping coefficients are referred to, respectively, as "direct" and "cross-coupled". The cross-coupled coefficients arise due to fluid rotation within the seal. The coefficient M accounts for the seal's added mass.

If a circular orbit of the form

$$X = A\cos\omega t, \qquad Y = A\sin\omega t \tag{2}$$

is assumed, Eq. (1) yields the following definition of force coefficients which are, respectively, parallel and perpendicular to the rotating displacement vector

$$\begin{aligned} F_r/A &= -K - c\omega + M\omega^2 \\ F_\theta/A &= k - C\omega \end{aligned} \tag{3}$$

Observe that the cross-coupled-stiffness coefficient k yields a "driving" tangential contribution in the direction of rotation, while the direct damping coefficient develops a drag force opposing the tangential velocity.

A prior investigation [6] examined five new "damper seal" configurations which were largely inspired by von Pragenau's work [1]. Von Pragenau's analysis predicts that a smooth-rotor/rough-stator combination will yield a reduced asymptotic fluid tangential velocity within the seal, which will, in turn, yield a reduction in the cross-coupled stiffness coefficient. A reduced cross-coupled stiffness coefficient reduces the destabilizing tangential driving force on the rotor, yields an increased net damping force, and generally enhances rotor stability and response. A subsequent and more comprehensive analysis by Childs and Kim [2], yields the same sort of encouraging predictions.

The results of [6] confirmed that damper seals could yield increased net damping coefficients and showed particularly encouraging results for the round-hole pattern configuration of figure 1. The report [7] provided test data for twelve additional round-hole-pattern seal configurations.

The results of [6] also included test results for the sawtooth-pattern, axially-grooved seal of figure 2. The teeth in the sawtooth-pattern cross section are directed against fluid rotation, with the intuitive expectation that this arrangement reduces the average circumferential fluid velocity and thereby reduces the cross-coupled-stiffness-coefficient, k. Test results for this seal showed a substantial increase in net damping as compared to a smooth seal; however, the leakage performance was only slightly better than a smooth seal and substantially worse than the hole pattern seal. The present report provides test data for eleven, sawtooth-pattern seals which are "inspired" by the original axially-grooved seal of figure 2, but have additional intermediate separators between the sawtooth pattern sections to improve leakage performance. The hope and expectation of this test program was that a sawtooth-pattern seal could be developed which retained or improved upon the damping performance suggested by the test results for the stator of figure 2, while sharply improving the leakage performance.

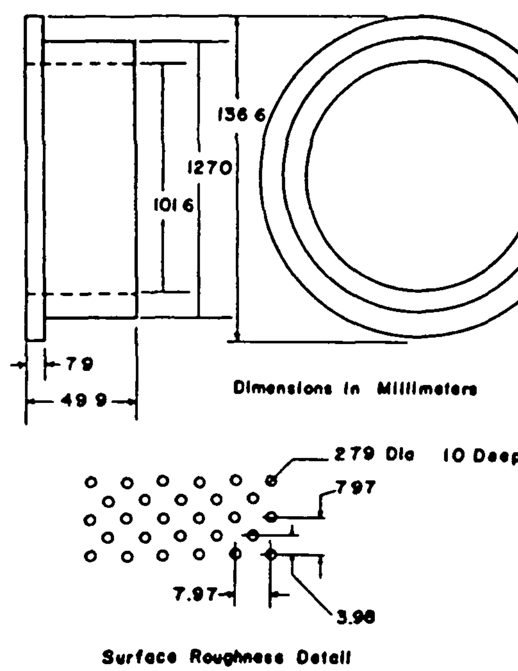


Figure 1. Round-hole pattern stator number insert number one.

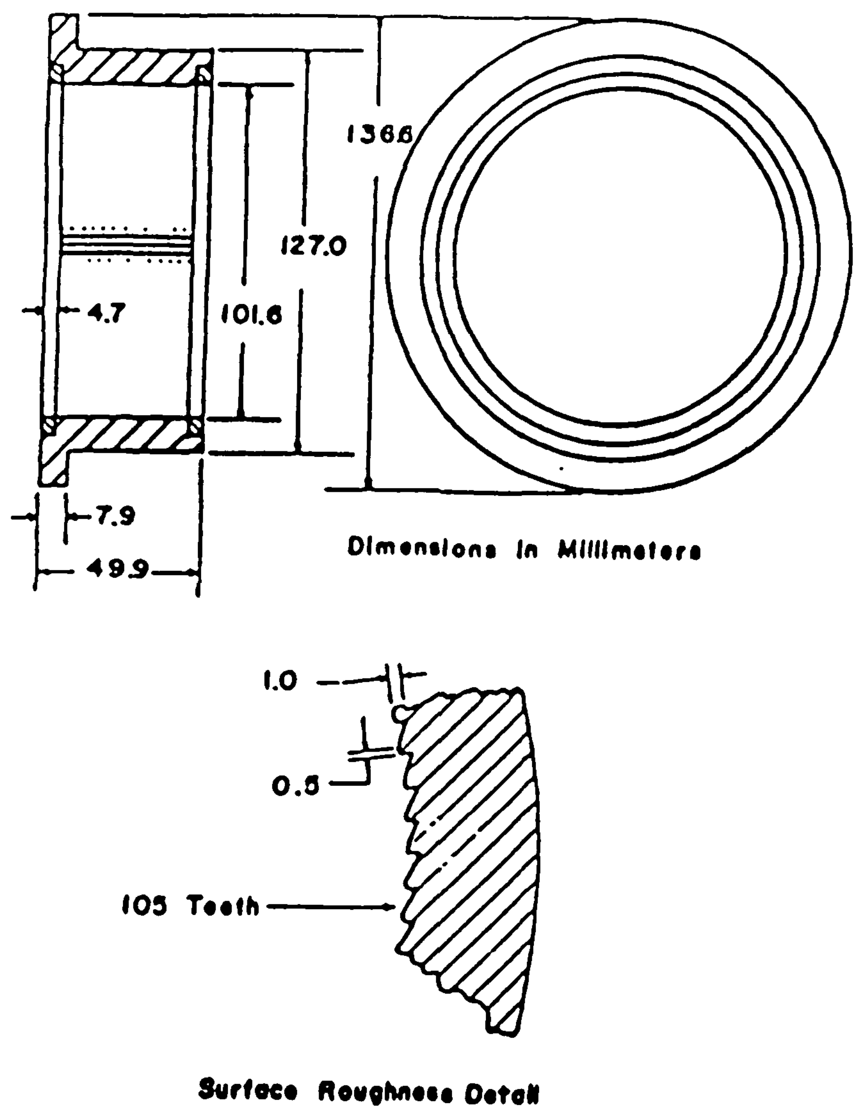


Figure 2. Axially-grooved, sawtooth-pattern stator insert with end seals.

TEST CONFIGURATIONS, CAPABILITY, AND RESULTS

Test Configurations

The seal test section is illustrated in figure 3 and is designed to accept candidate seal inserts. All seals tested use a smooth rotor and have a constant minimum clearance, i.e., no taper. Figure 4 illustrates the assembly procedure for the sawtooth-pattern seal. The sawtooth-pattern sections are pressed into a stainless-steel housing and separated by dams. A brass retaining ring at the seal entrance holds the seal-ring/dam assembly together.

All stators tested had 4 inch (101.6 mm) internal diameters, were 2 inches (50 mm) long, and had .020 in (.508 mm) minimum radial clearances.

Figure 5 illustrates the dimensions and arrangements for stators 1 through 4. Observe that the axial-grooves in the seal section are aligned for seals 1 and 3 (straight), but are staggered for seals 2 and 4. The groove-depth (tooth height) of 2.54 mm is characteristically large for these four stators.

Figure 6 illustrates the dimensions for seals 5 through 7. By comparison to figure 2, seal 5 has the same cross-section as the original axial-grooved seal. The three, stator cross sections of figure 6 differ only in the number of teeth or grooves. For these stators, the groove-depth to minimum-clearance ratio, h/C_r, is two.

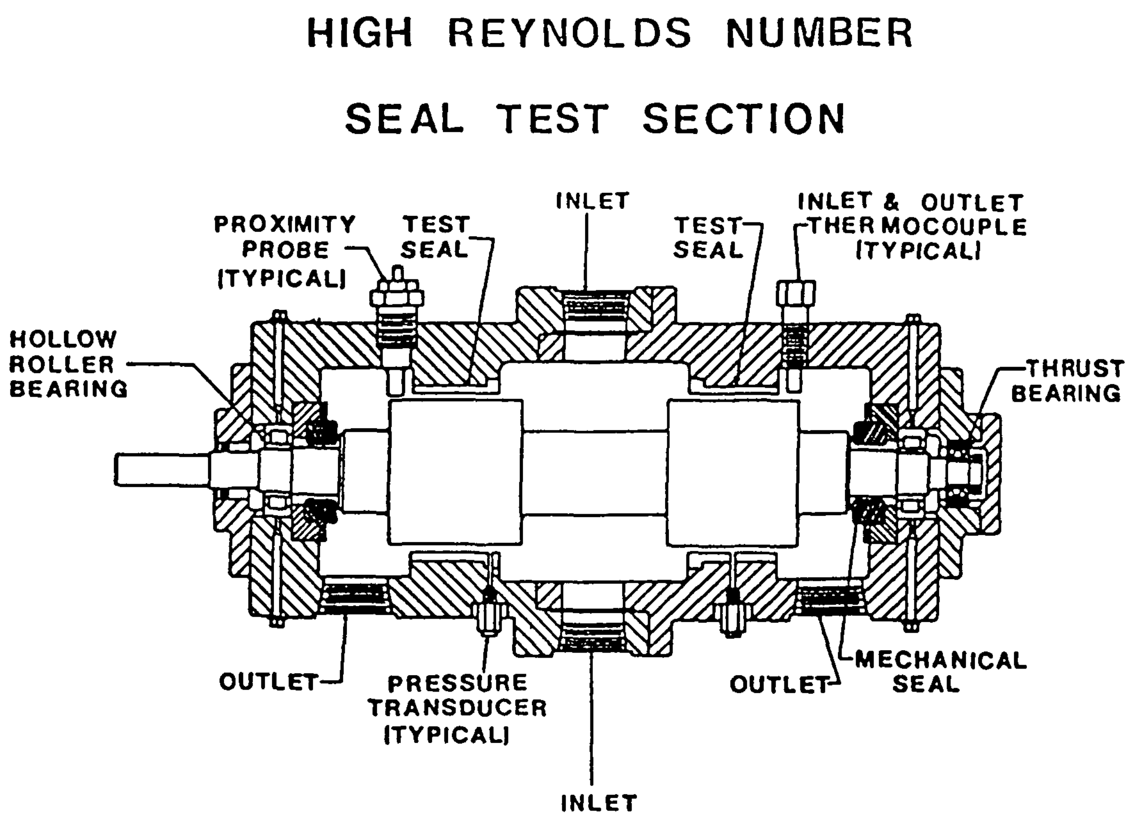


Figure 3. High-Reynolds-Number seal test section.

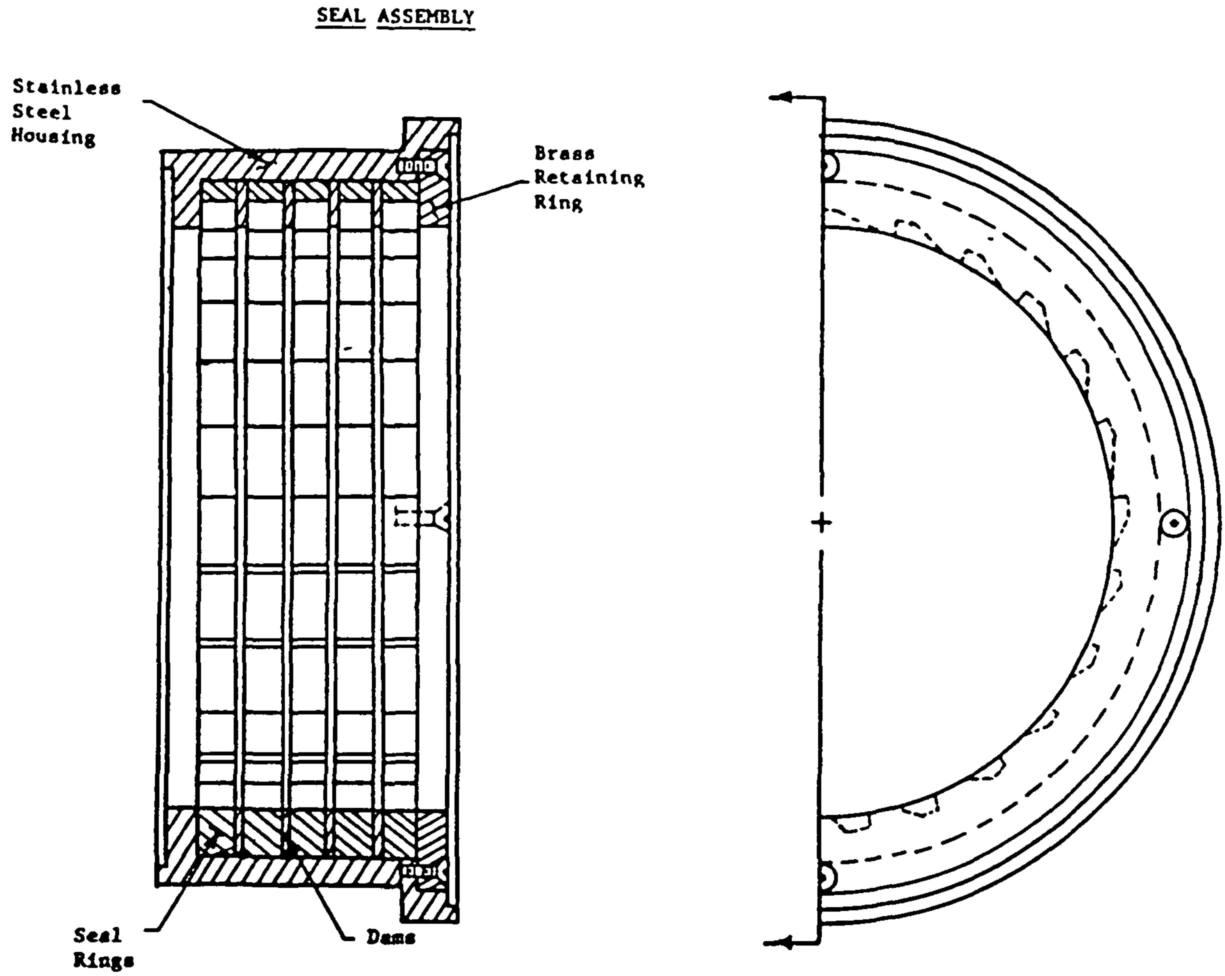


Figure 4. Cross-section of sawtooth-pattern stator.

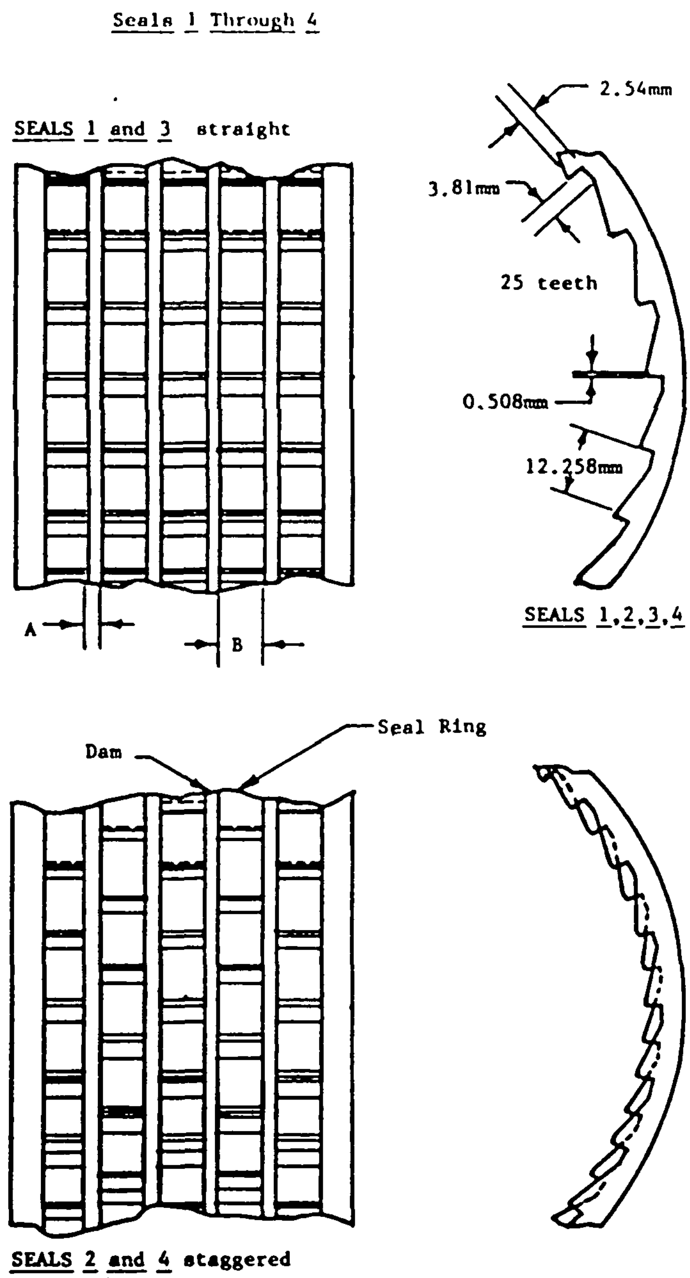


Figure 5. Schematic for sawtooth-pattern stators 1 through 4.

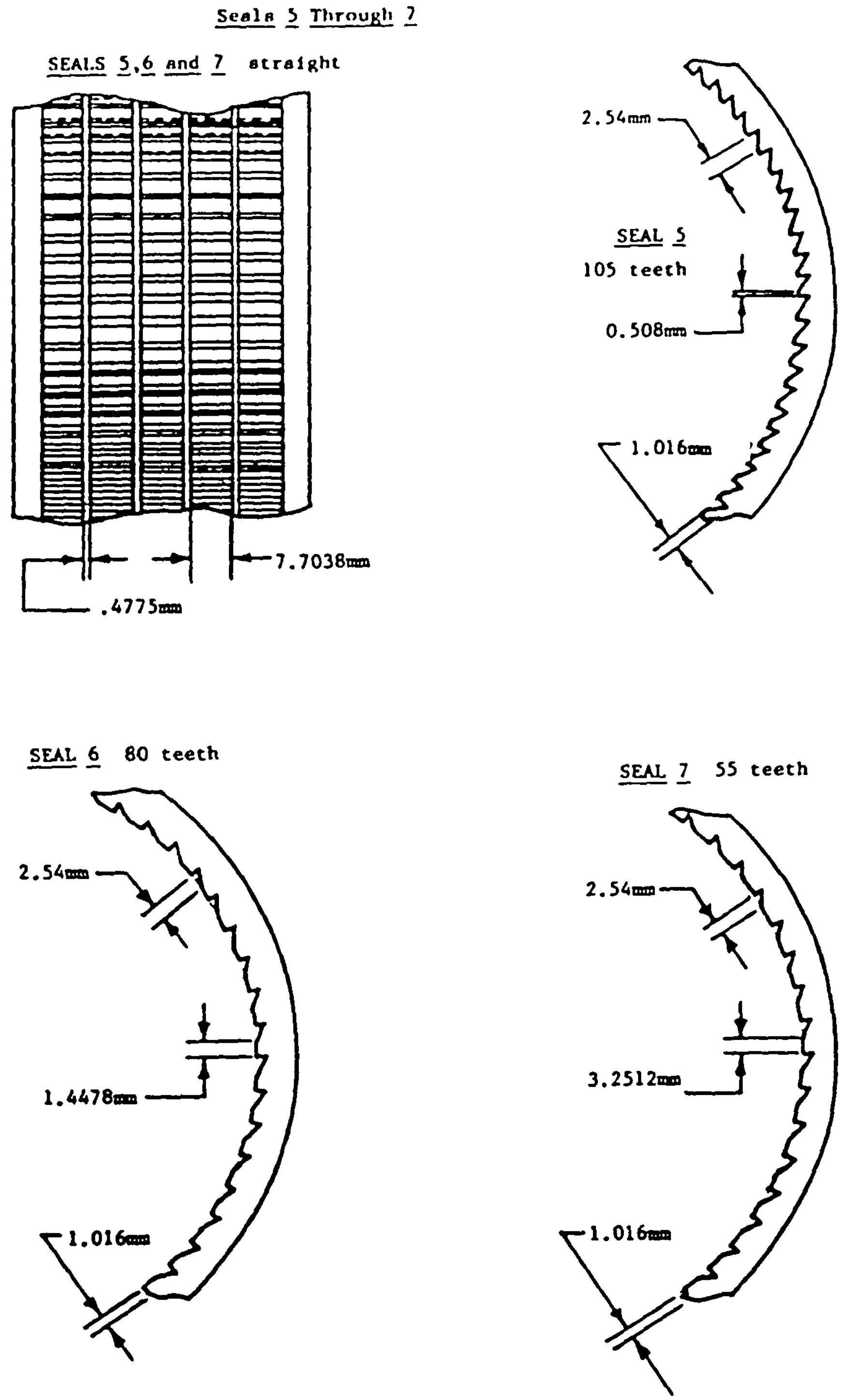


Figure 6. Schematic for sawtooth-pattern stators 5 through 7.

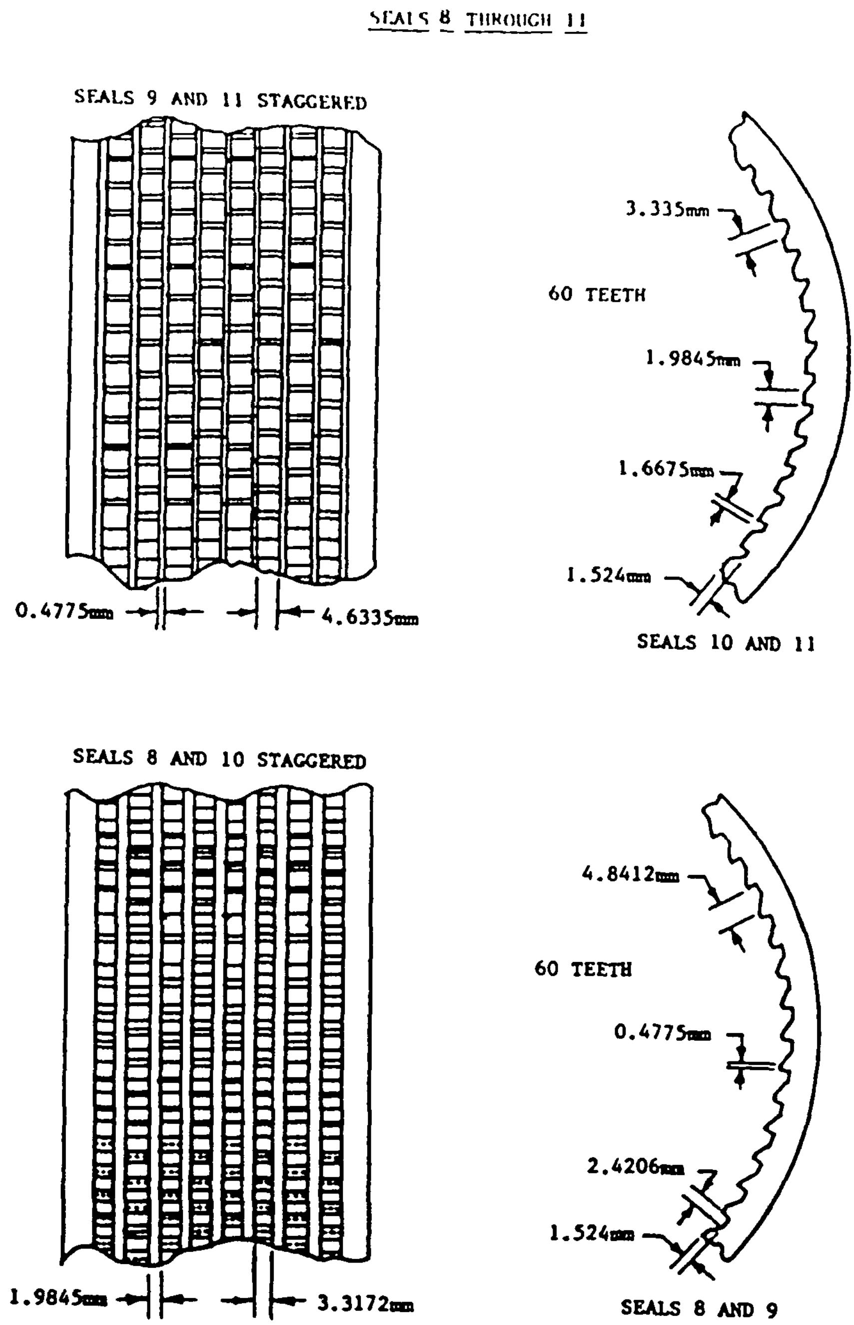


Figure 7. Schematic for sawtooth-pattern stators 8 through 11.

Figure 7 illustrates the dimensions of seals 9 through 11. The h/C_r ratios for this group of seals is 3.0.

The parameter,

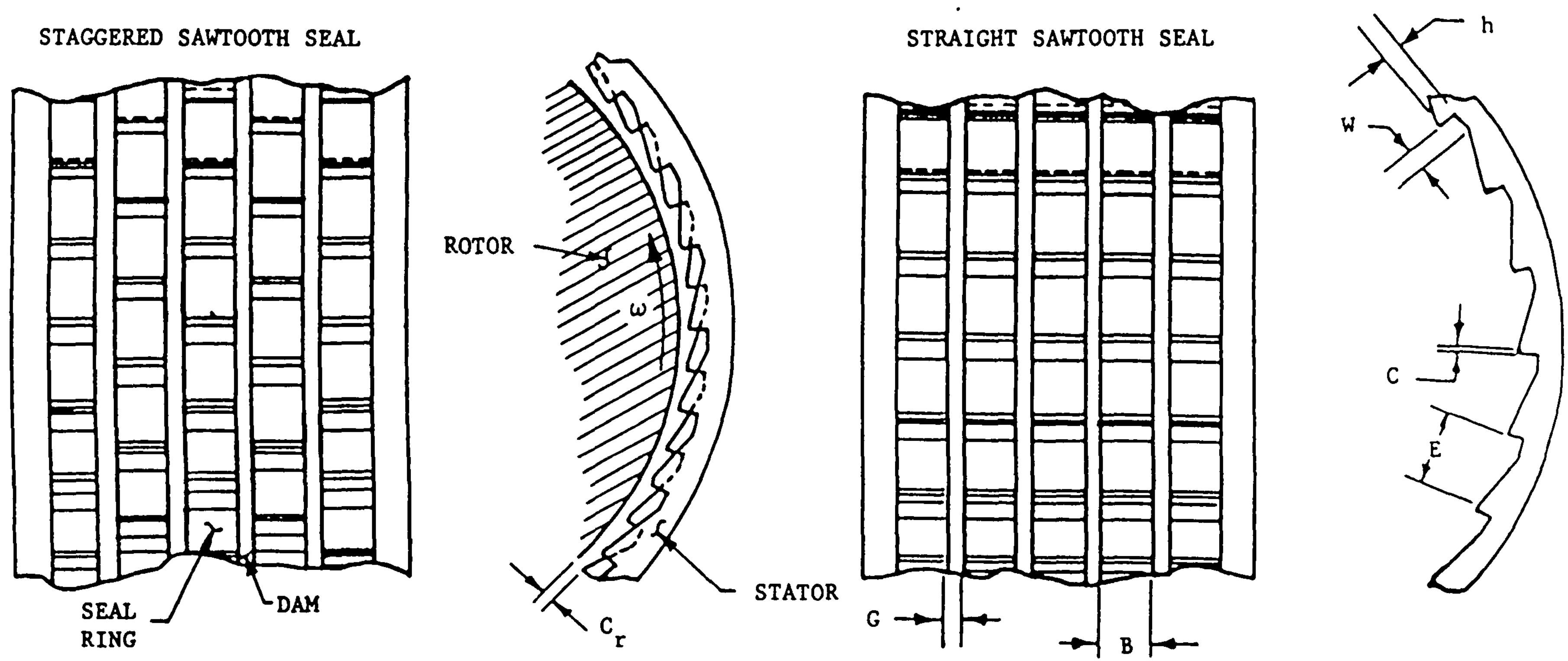
$$\gamma = \frac{\text{hole area}}{\text{total area}}$$

was easily calculated for the round-hole pattern seals. For the present seals, the area of a single "hole" is defined to be $A_h = BXE$. Table 1 provides. the dimensions, and h/C_r and γ ratios for all of the sawtooth-pattern stators.

Test and Data Capability

The rotor segments of the test seal are mounted eccentrically on the rotor of figure 2 with the eccentricity A. Hence, rotor rotation generates a synchronously precessing pressure field. Axially spaced, strain-gauge, pressure transducers are provided to measure the transient pressure field, and the transient pressure measurements are recorded and integrated to define F_r/A, F_θ/A, and $|F|$. In any test, five to ten cycles of data, containing on the order of 2,000 data points, are analyzed. Each data point yields a calculated value for F_r/A, F_θ/A and $|F|$, and average and standard-deviation values are calculated for the test case. Observe from Eq. (3) that the test apparatus yields only the <u>net</u> radial and tangential force coefficients and can not be used to separately identify the seal coefficients.

The analysis of von Pragenau [1] and Childs and Kim [2] indicates that the seal rotor and stator roughness are important in defining the cross-coupled stiffness coefficient k and net-damping-force coefficient



SEAL	TEETH	SEAL RINGS	DAMS	TYPE	h (mm)	W (mm)	C (mm)	E (mm)	G (mm)	B (mm)	γ	h/C_r
1	25	5	4	straight	2.54	3.81	0.508	12.258	4.9225	4.1478	.40	5.0
2	25	5	4	staggered	2.54	3.81	0.508	12.258	4.9225	4.1478	.40	5.0
3	25	5	4	straight	2.54	3.81	0.508	12.258	0.4775	7.7038	.74	5.0
4	25	5	4	staggered	2.54	3.81	0.508	12.258	0.4775	7.7038	.74	5.0
5	105	5	4	straight	1.016	0.0	0.508	2.54	0.4775	7.7038	.64	2.0
6	80	5	4	straight	1.016	0.0	1.4478	2.54	0.4775	7.7038	.49	2.0
7	55	5	4	straight	1.016	0.0	3.2512	2.54	0.4775	7.7038	.34	2.0
8	60	8	7	staggered	1.524	2.4206	0.4775	4.8412	1.9845	3.3172	.48	3.0
9	60	8	7	staggered	1.524	2.4206	0.4774	4.8412	0.4775	4.6355	.68	3.0
10	60	8	7	staggered	1.524	1.6675	1.9845	3.3350	1.9845	3.3172	.33	3.0
11	60	8	7	staggered	1.524	1.6675	1.9845	3.3350	0.4775	4.6355	.47	3.0

Table 1. Dimensions of sawtooth-pattern stators.

F_θ/A. For homogeneous roughness, estimates for the relative roughness parameters can be obtained from measured results for the axial pressure gradient and leakage rate. The required data, consisting of the supply and discharge pressures and pressure measurements at axial locations throughout the seal, are sampled, averaged, and recorded immediately before transient data are recorded. For homogeneous-roughness stators, this data can be used as input data for predictions of seal rotordynamic coefficients. However, no analytical model presently exists for the inhomogeneous and discontinuous roughness pattern presented by these sawtooth stators.

For a given seal configuration, a test matrix is carried out with variations in the flowrate (axial Reynolds number) and shaft rotational speed. The flowrate is varied from a minimum value, which is sufficient to yield adequate signal-to-noise ratios of the transient pressure measurements, out to the maximum flow capability of the circuit. Shaft rotation speed is incremented from approximately 1,000 rpm to 7,200 rpm. In a given test series, the axial Reynolds number is held constant and the running speed incremented.

For a given test, the following two types of data are secured:

(a) steady-state "input" data consisting of the pressure differential, average fluid density and viscosity, mass leakage rate, and rotational speed, and

(b) "output" data consisting of F_r/A, F_θ/A, $|F|$ versus the axial Reynolds number and shaft running speed.

The tables of Appendices B and C provide this type of data for each test of each seal configuration.

DYNAMIC TEST RESULTS

Figure 8 through 18 illustrate measured results for F_r/A and F_θ/A versus R_a and ω for the sawtooth-pattern seals. Each curve of these figures corresponds to a fixed axial Reynolds number, R_a. Appendix B contains the data presented in these figures.

The results of figures 8 through 18 generally follow the predictions of Eq. (3). The radial force coefficients starts at a negative valve for low running speeds and increases in an approximate quadratic fashion as ω increases. The tangential force coefficients is an approximate linear function of ω.

An inspection of Eqs. (3) suggest that sufficient independent equations could be obtained to calculate all the rotordynamic coefficients by simply testing at three running speeds. However, the fact that the coefficients depend on ω precludes this approach. While K, C, and M are weak functions of ω through their dependence on σ, the "cross-coupled" coefficients k and c are linear functions of ω. In fact, if the fluid is prerotated prior to entering the seal such that the inlet tangential velocity is $U_{\theta o} = R\omega/2$, then theory predicts that $k = C\omega/2$, $c = M\omega$, and

$$F_r/A = -K, \; F_\theta/A = -C\omega/2 \tag{4}$$

The present test apparatus provides no intentional prerotation, and the expected result is of the form

$$k = b_1 C\omega/2, \; b_1<1$$

$$c = b_2 M\omega, \; b_2<1 \tag{5}$$

$$F_\theta/A = -C_{ef}\,\omega = -C(1-b_1/2)\omega$$

$$F_r/A = -K_{ef} + M_{ef}\,\omega^2 = -K + M(1-b_2)\omega^2 \tag{6}$$

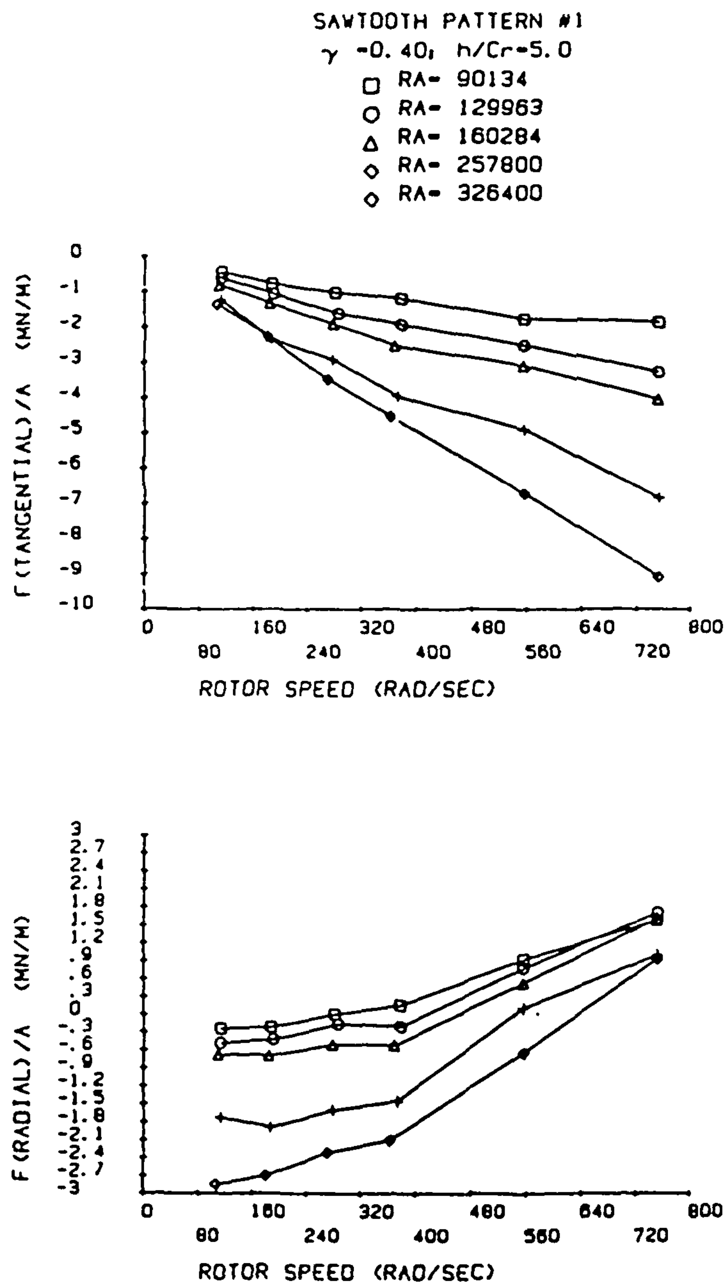


Figure 8. Radial and tangential force coefficients for sawtooth stator 1.

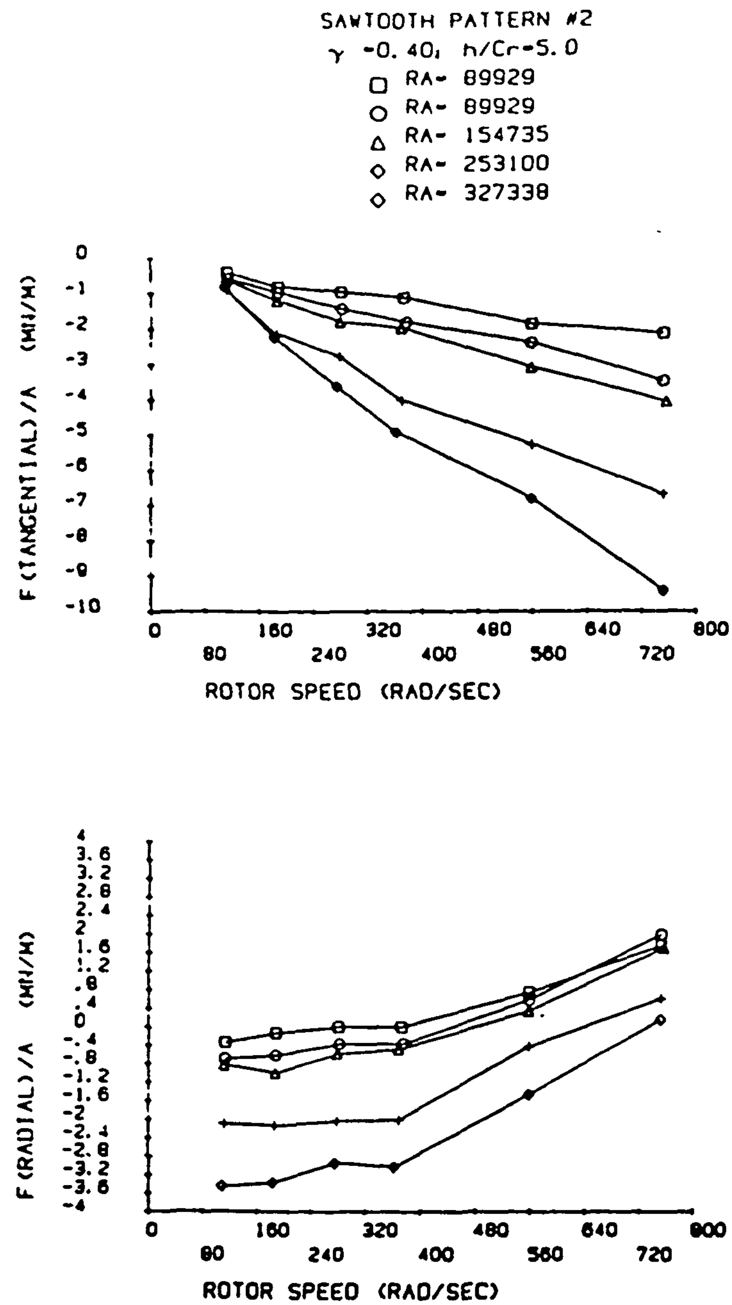


Figure 9. Radial and tangential force coefficients for sawtooth stator 2.

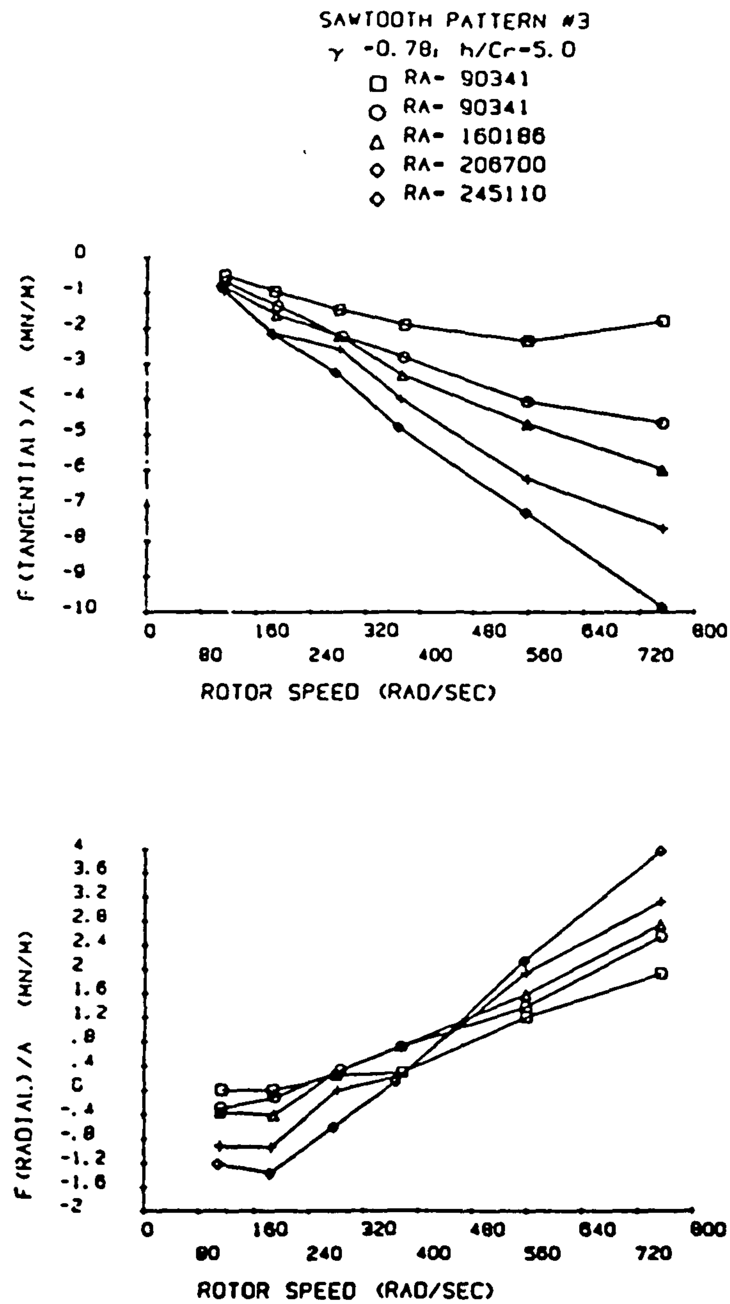


Figure 10. Radial and tangential force coefficients for sawtooth stator 3.

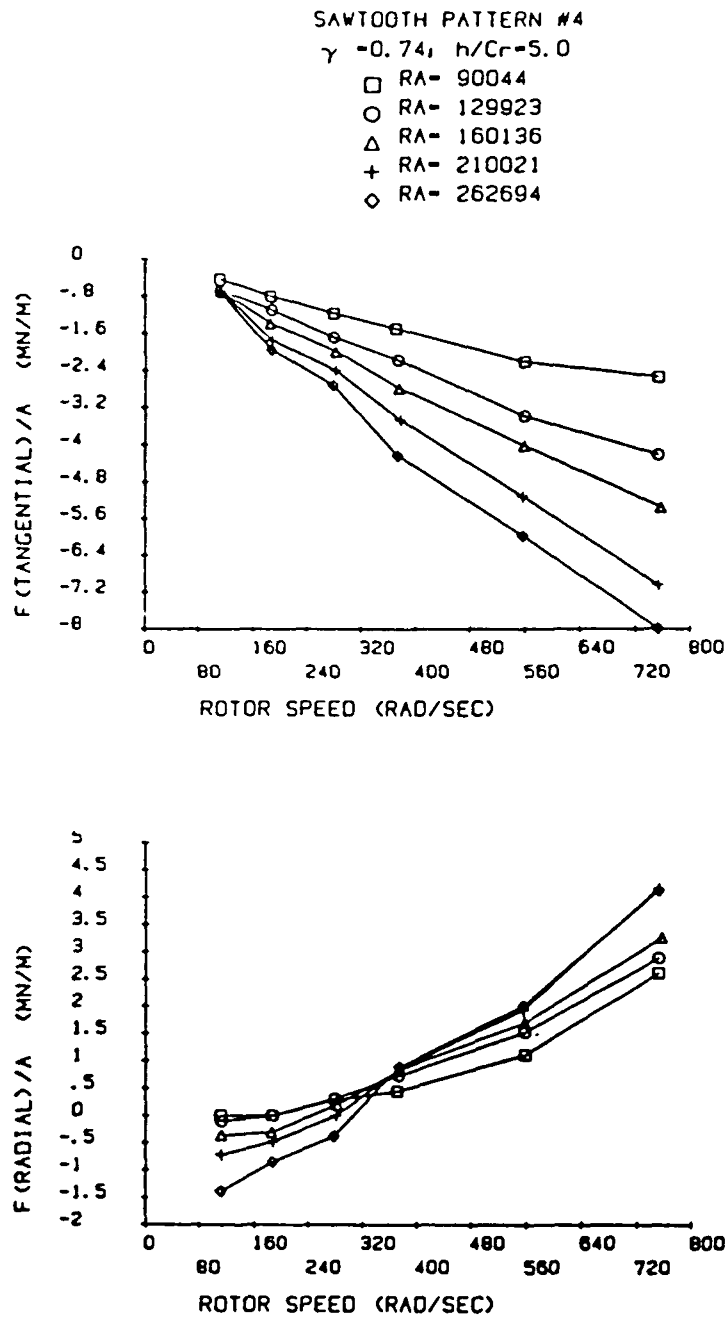


Figure 11. Radial and tangential force coefficients for sawtooth stator 4.

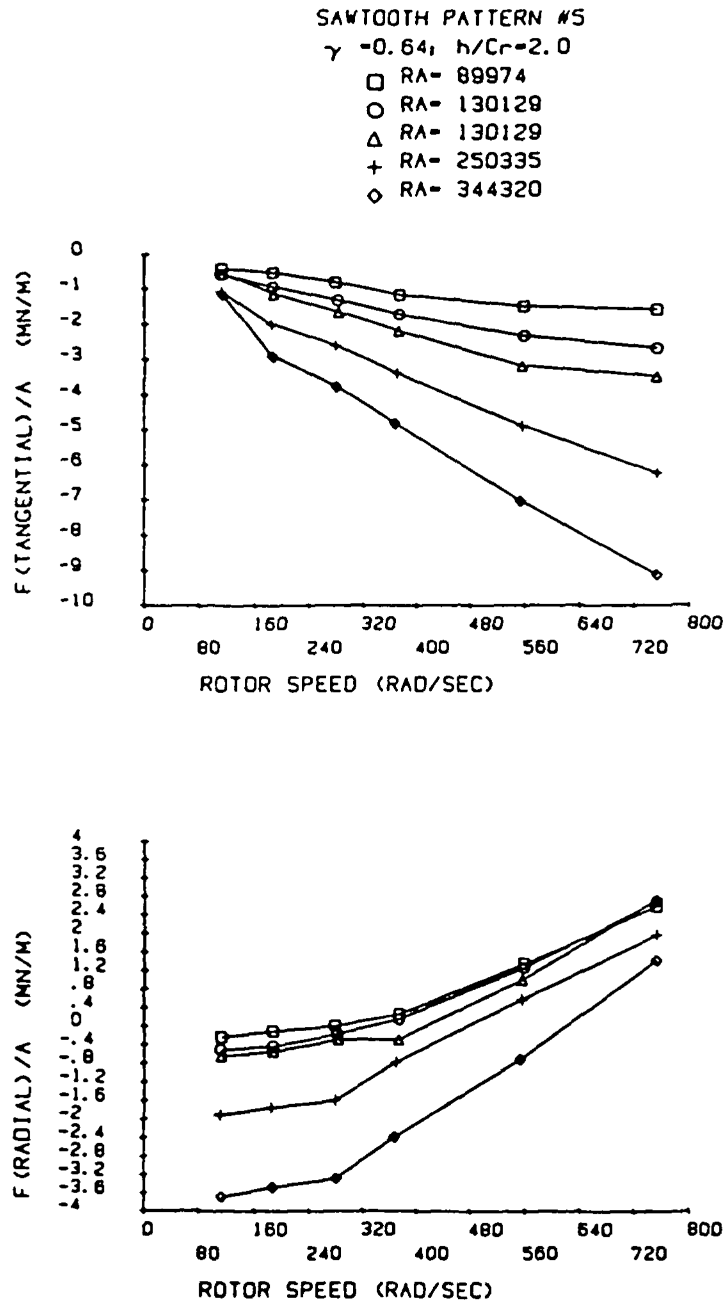


Figure 12. Radial and tangential force coefficients for sawtooth stator 5.

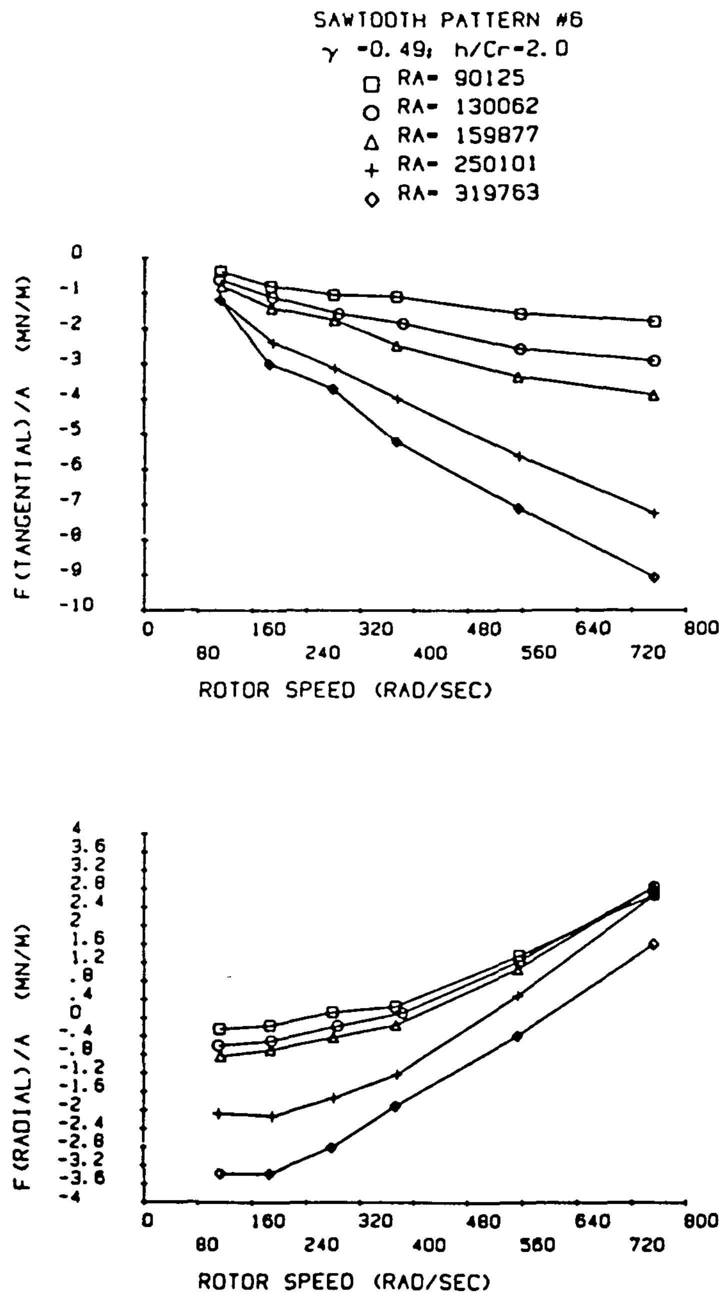


Figure 13. Radial and tangential force coefficients for sawtooth stator 6.

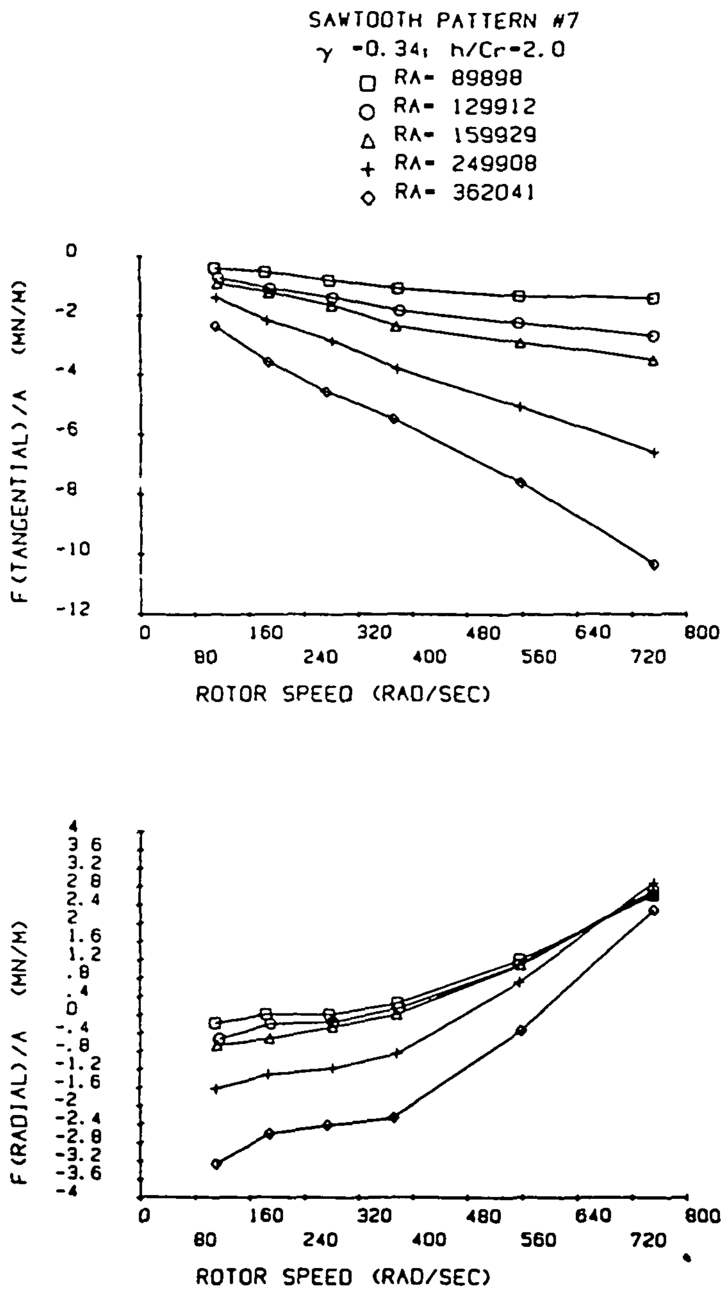


Figure 14. Radial and tangential force coefficients for sawtooth stator 7.

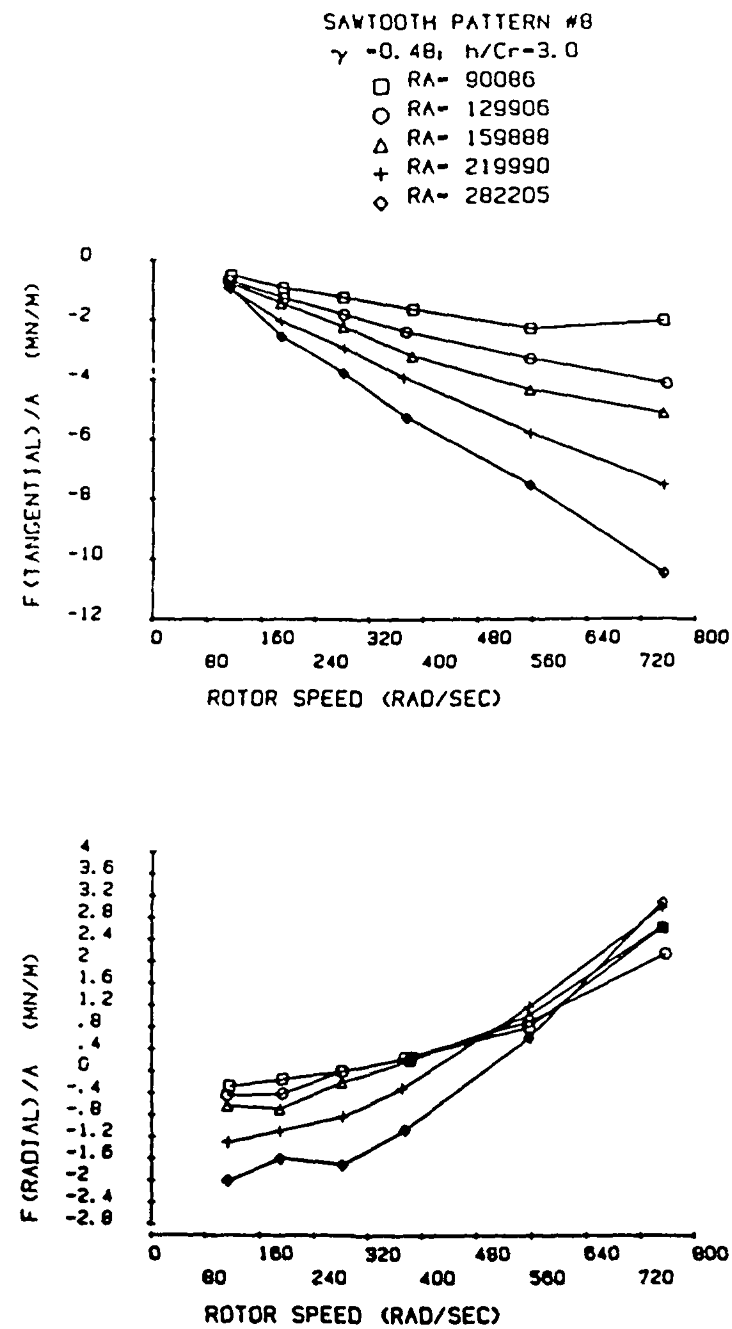


Figure 15. Radial and tangential force coefficients for sawtooth stator 8.

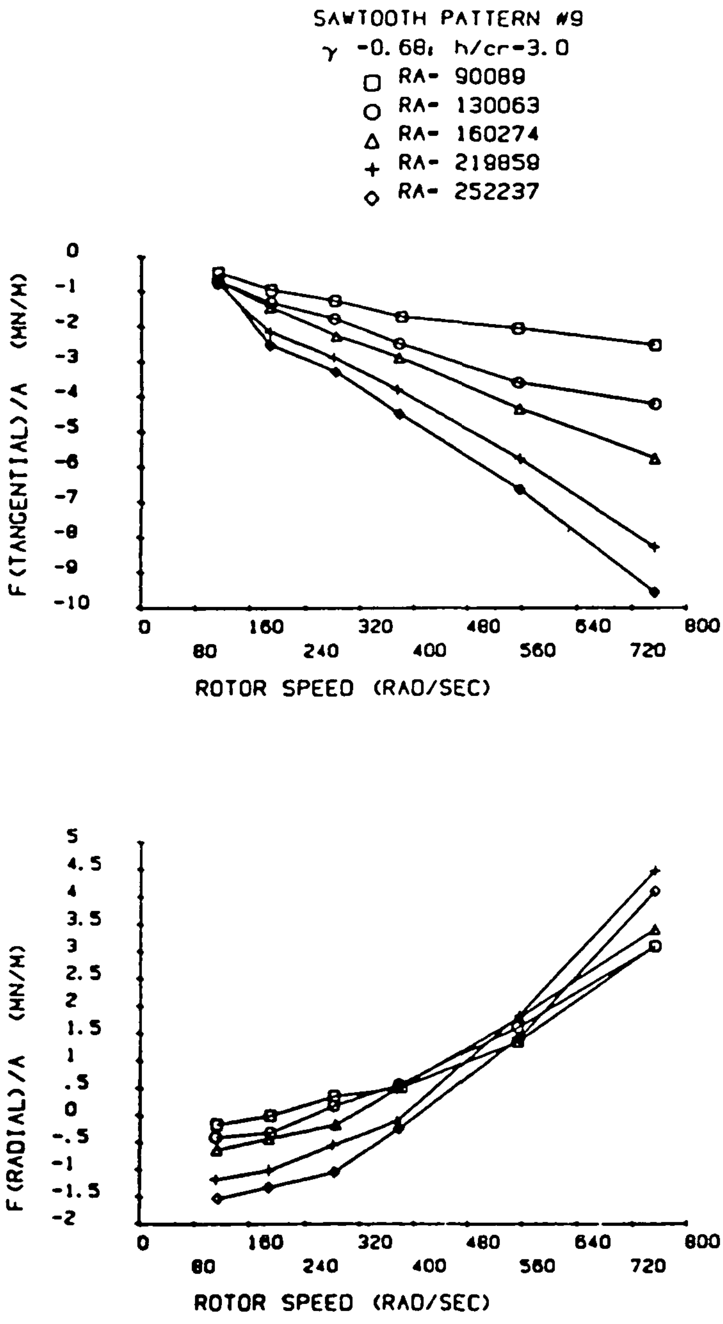


Figure 16. Radial and tangential force coefficients for sawtooth stator 9.

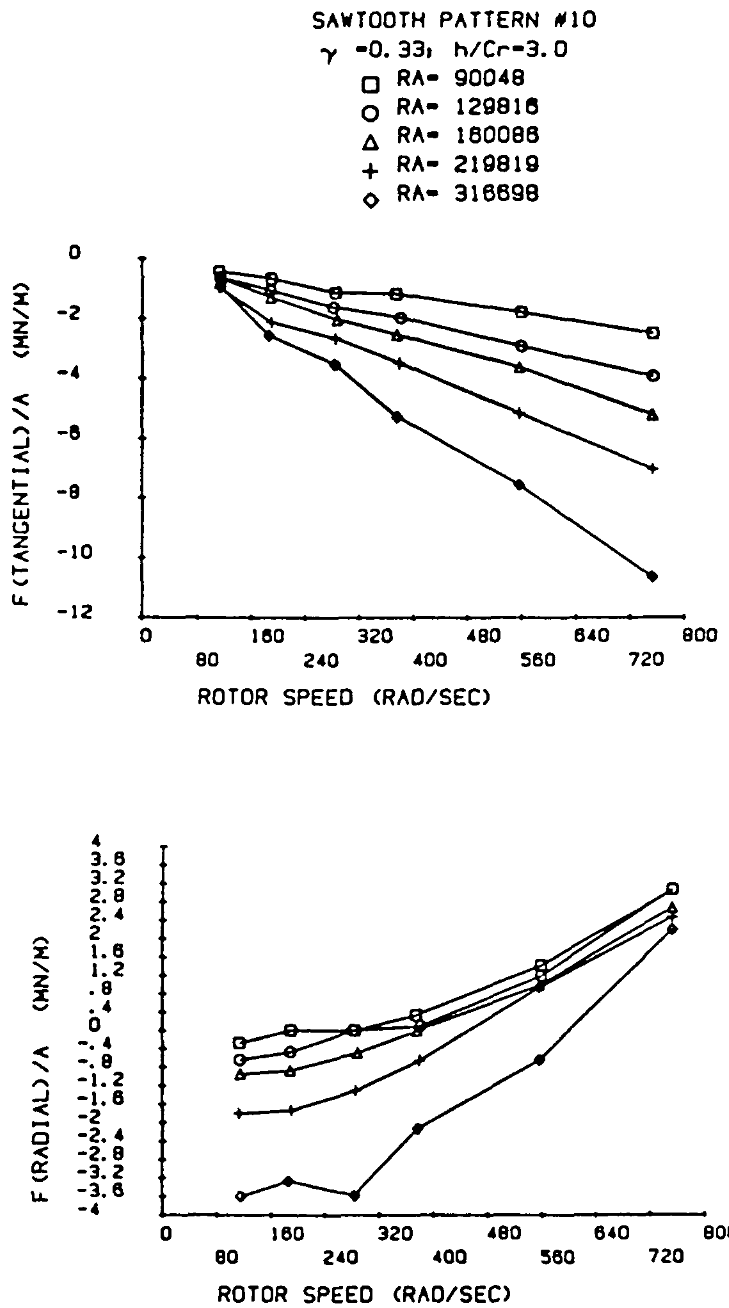


Figure 17. Radial and tangential force coefficients for sawtooth stator 10.

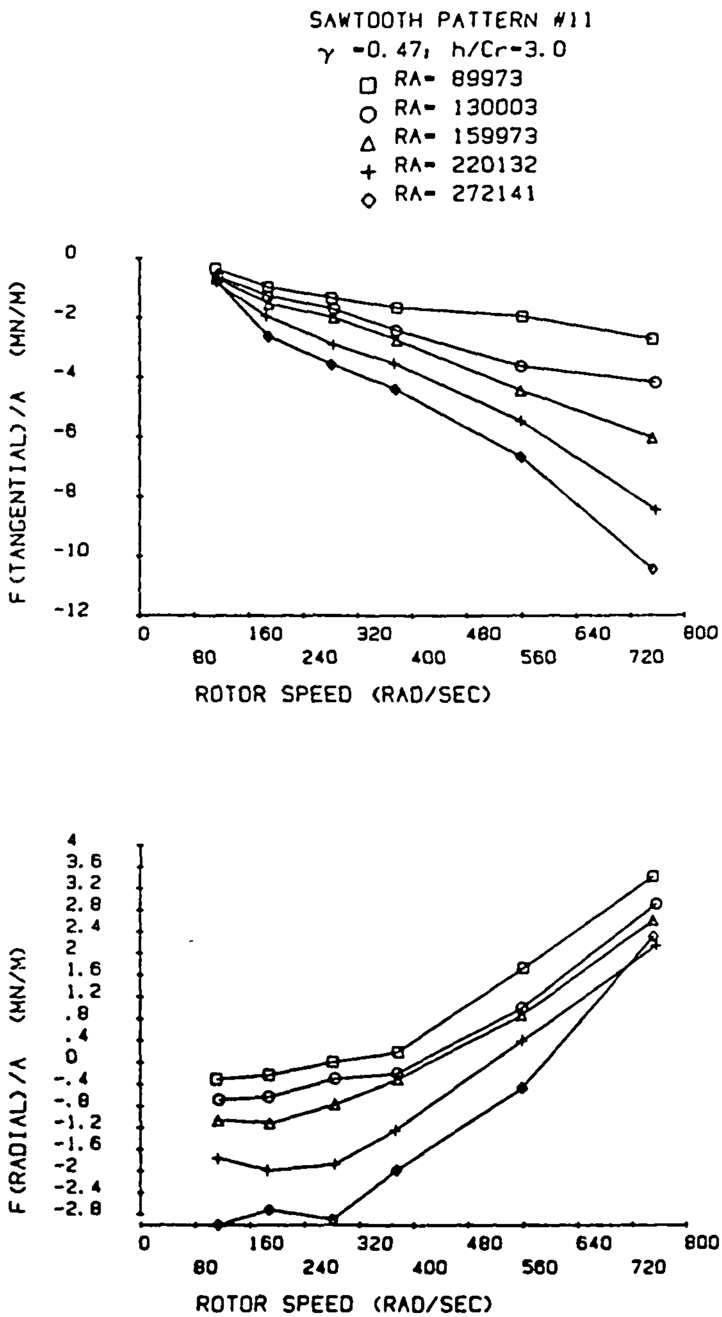


Figure 18. Radial and tangential force coefficients for sawtooth stator 11.

The term C_{ef} denotes the "net damping coefficient" resulting from the drag force $C\omega A$ and the forward whirl excitation force kA. Note that the procedure of curvefitting the data with respect to ω eliminates the running-speed dependency. Further, K_{ef} is the zero-running speed intercept of the F_r/A versus ω curve, and C_{ef} is the slope of the F_θ/A versus ω curve. Experimentally-determined values are presented in tables 2(a), 2(b) and 2(c) for K_{ef}, C_{ef}, and M_{ef}.

From a rotordynamics viewpoint, K_{ef} and C_{ef} can be used for direct comparison of the performance of seal configurations at the same pressure differential. For leakage comparison, the leakage coefficient is defined using the conventional discharge-coefficient definition

$$\Delta P = C_d \frac{\rho V^2}{2} \tag{7}$$

which yields

$$\dot{Q} = 2\pi R C_r V = \left(\frac{Cr}{R}\right) C_d^{-1/2} \cdot 2\pi R^2 \sqrt{\frac{2\Delta P}{\rho}} = C_L \cdot 2\pi R^2 \sqrt{\frac{2\Delta P}{\rho}}$$

Hence,

$$C_L = \left(\frac{C_r}{R}\right) C_d^{-1/2} = \dot{Q} \left(2\pi R^2 \sqrt{\frac{2\Delta P}{\rho}}\right) \tag{8}$$

The coefficient C_L is a nondimensional relative measure of the leakage to be expected through seals having the same radius.

Figures 19 through 27 illustrate K_{ef}, C_{ef}, and C_L versus ΔP for all of the sawtooth-pattern stators. For comparison purposes, results are also given in these figures for a smooth stator and the hole-pattern stator with maximum net damping.

	KEF(EXP)	CEF(EXP)	MEF(EXP)
SAWTOOTH PATTERN #1 h/Cr= 5.0			
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.40			
RA= .9013E 05	.4126E 06	2254.	2.542
RA= .1300E 06	.4918E 06	4021.	4.592
RA= .1603E 06	.6002E 06	4878.	6.008
RA= .2578E 06	.1971E 07	8255.	5.444
RA= .3264E 06	.3003E 07	.1190E 05	6.092
SAWTOOTH PATTERN #2 h/Cr= 5.0			
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.40			
RA= .8993E 05	.1942E 06	2712.	4.935
RA= .1300E 06	.5279E 06	4362.	6.886
RA= .1598E 06	.8402E 06	5166.	5.989
RA= .2531E 06	.2090E 07	8746.	7.178
RA= .3273E 06	.3417E 07	.1286E 05	7.825
SAWTOOTH PATTERN #3 h/Cr= 5.0			
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.74			
RA= .9034E 05	.2351E 06	2174.	3.060
RA= .1300E 06	.6202E 06	6327.	2.124
RA= .1602E 06	.9123E 06	8093.	1.765
RA= .2067E 06	.1669E 07	.1061E 05	2.016
RA= .2451E 06	.1942E 07	.1387E 05	5.865
SAWTOOTH PATTERN #4 h/Cr= 5.0			
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.74			
RA= .9004E 05	-.8431E 05	3352.	6.171
RA= .1299E 06	.3121E 06	5634.	4.265
RA= .1601E 06	.7688E 06	7151.	3.653
RA= .2101E 06	.1082E 07	9724.	5.865
RA= .2620E 06	.2142E 07	.1116E 05	2.483

Table 2(a). Measured values for K_{ef}, C_{ef}, and M_{ef} for sawtooth stators 1 through 4.

		KEF(EXP)	CEF(EXP)	MEF(EXP)

SAWTOOTH PATTERN #5 h/Cr= 2.0
105 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.64

RA=	.8997E 05	.2567E 06	1989.	5.726
RA=	.1301E 06	.5894E 06	3352.	6.118
RA=	.1600E 06	.4427E 06	4687.	8.840
RA=	.2503E 06	.2352E 07	7910.	4.534
RA=	.3443E 06	.4025E 07	.1197E 05	7.946

SAWTOOTH PATTERN #6 h/Cr= 2.0
80 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.49

RA=	.9012E 05	.2703E 06	2110.	5.830
RA=	.1301E 06	.6323E 06	3592.	6.826
RA=	.1599E 06	.8114E 06	4898.	7.631
RA=	.2501E 06	.2203E 07	9241.	9.925
RA=	.3198E 06	.3971E 07	.1183E 05	5.796

SAWTOOTH PATTERN #7 h/Cr= 2.0
55 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.34

RA=	.8990E 05	.3352E 05	1691.	6.874
RA=	.1299E 06	.3809E 06	3083.	7.041
RA=	.1599E 06	.6550E 06	4179.	6.819
RA=	.2499E 06	.1460E 07	8072.	10.23
RA=	.3620E 06	.3007E 07	.1203E 05	11.36

Table 2(b). Measured values for K_{ef}, C_{ef}, and M_{ef} for sawtooth stators 5 through 7.

		KEF(EXP)	CEF(EXP)	MEF(EXP)
SAWTOOTH PATTERN #8			h/Cr= 3.0	
60 TEETH, TOOTH DEPTH=1.524mm, GAMMA=0.48				
RA=	.9009E 05	-.2086E 05	2554.	7.929
RA=	.1299E 06	.5965E 06	5342.	3.759
RA=	.1599E 06	.7869E 06	6954.	5.777
RA=	.2200E 06	.1489E 07	.1018E 05	7.125
RA=	.2822E 06	.1804E 07	.1449E 05	11.84
SAWTOOTH PATTERN #9			h/Cr= 3.0	
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.68				
RA=	.9009E 05	.6691E 05	3090.	6.841
RA=	.1301E 06	.6953E 06	5632.	4.512
RA=	.1603E 06	.9550E 06	7796.	5.498
RA=	.2199E 06	.1218E 07	.1121E 05	11.46
RA=	.2522E 06	.1599E 07	.1316E 05	11.18
SAWTOOTH PATTERN #10			h/Cr= 3.0	
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.33				
RA=	.9005E 05	.1809E 06	3110.	7.397
RA=	.1298E 06	.5707E 06	5061.	7.625
RA=	.1601E 06	.1128E 07	6865.	5.947
RA=	.2198E 06	.2292E 07	9164.	5.290
RA=	.3167E 06	.3600E 07	.1477E 05	12.37
SAWTOOTH PATTERN #11			h/Cr= 3.0	
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.47				
RA=	.8997E 05	.2242E 06	3327.	9.012
RA=	.1300E 06	.5037E 06	5685.	8.991
RA=	.1600E 06	.1169E 07	8292.	7.561
RA=	.2201E 06	.1868E 07	.1125E 05	9.716
RA=	.2721E 06	.2729E 07	.1404E 05	13.50

Table 2(c). Measured values for K_{ef}, C_{ef}, and M_{ef} for sawtooth stators 8 through 11.

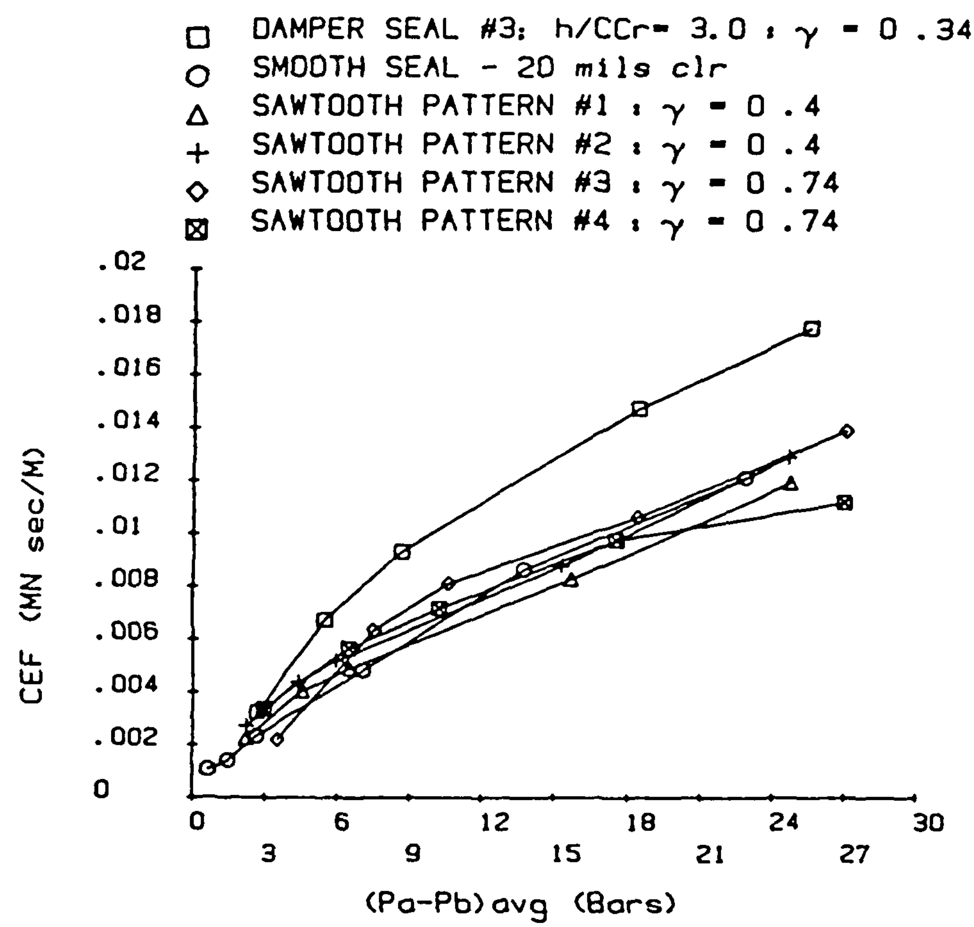


Figure 19. C_{ef} versus ΔP for sawtooth stators 1 through 4, a smooth stator, and the optimum-damping round-hole-pattern stator.

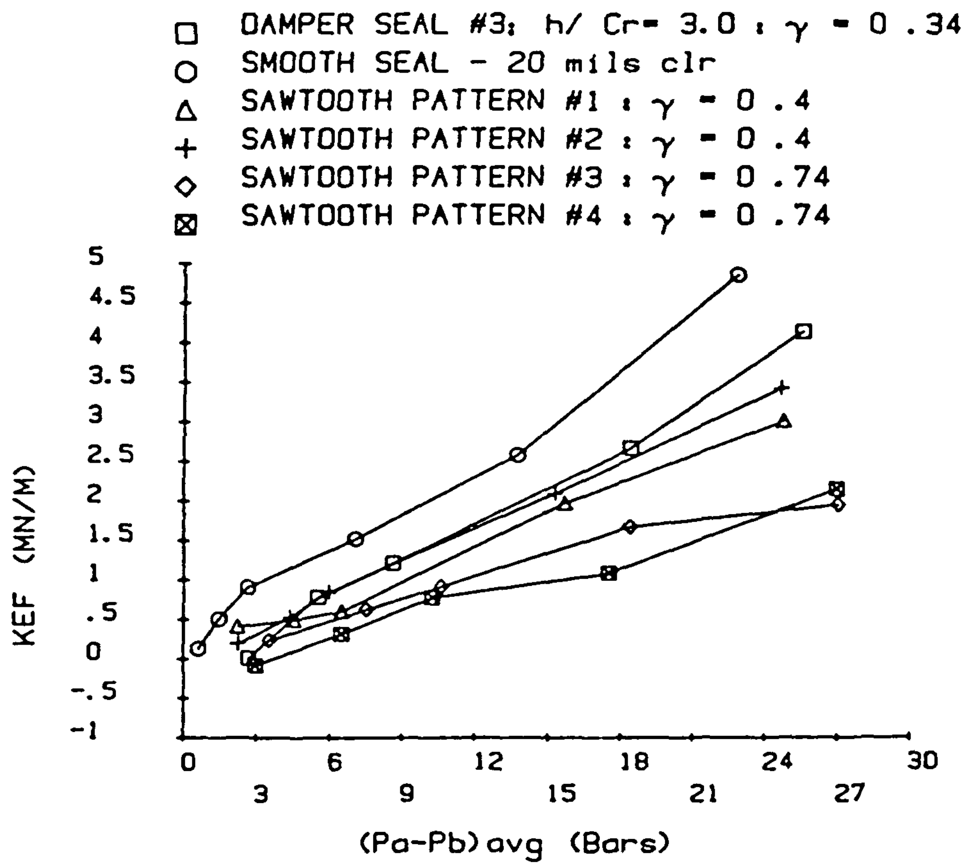


Figure 20. K_{ef} **versus** ΔP **for sawtooth stators 1 through 4, a smooth stator, and the optimum-damping round-hole-pattern stator.**

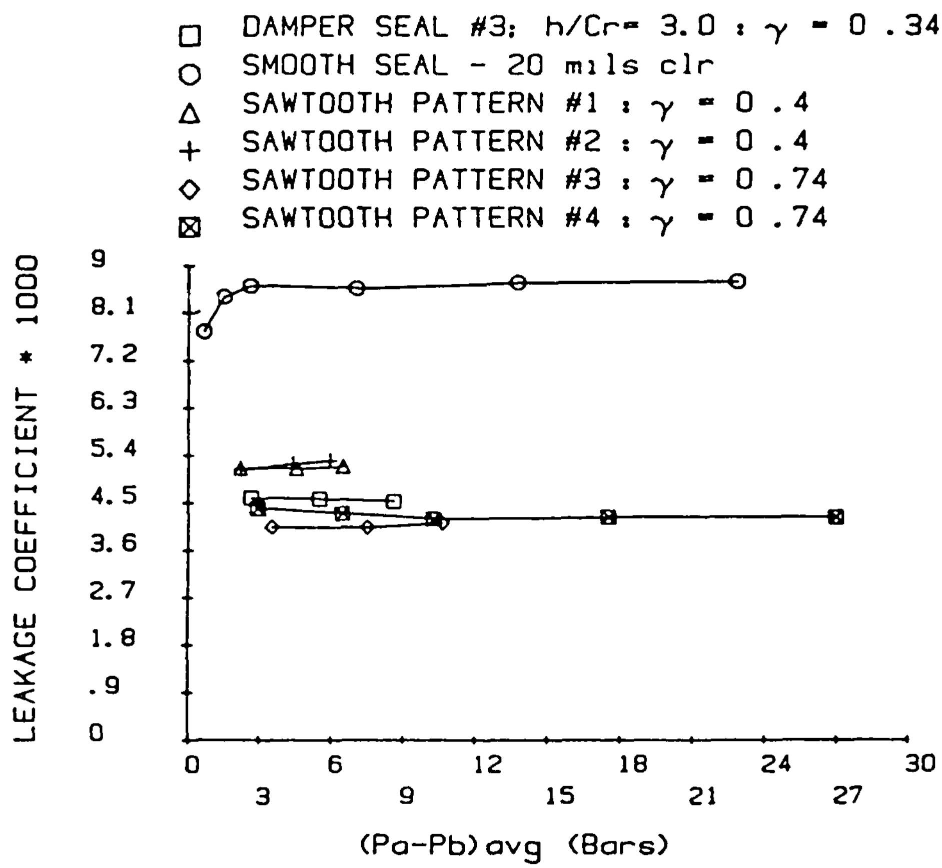


Figure 21. C_L versus ΔP for sawtooth stators 1 through 4, a smooth stator, and the optimum-damping round-hole-pattern stator.

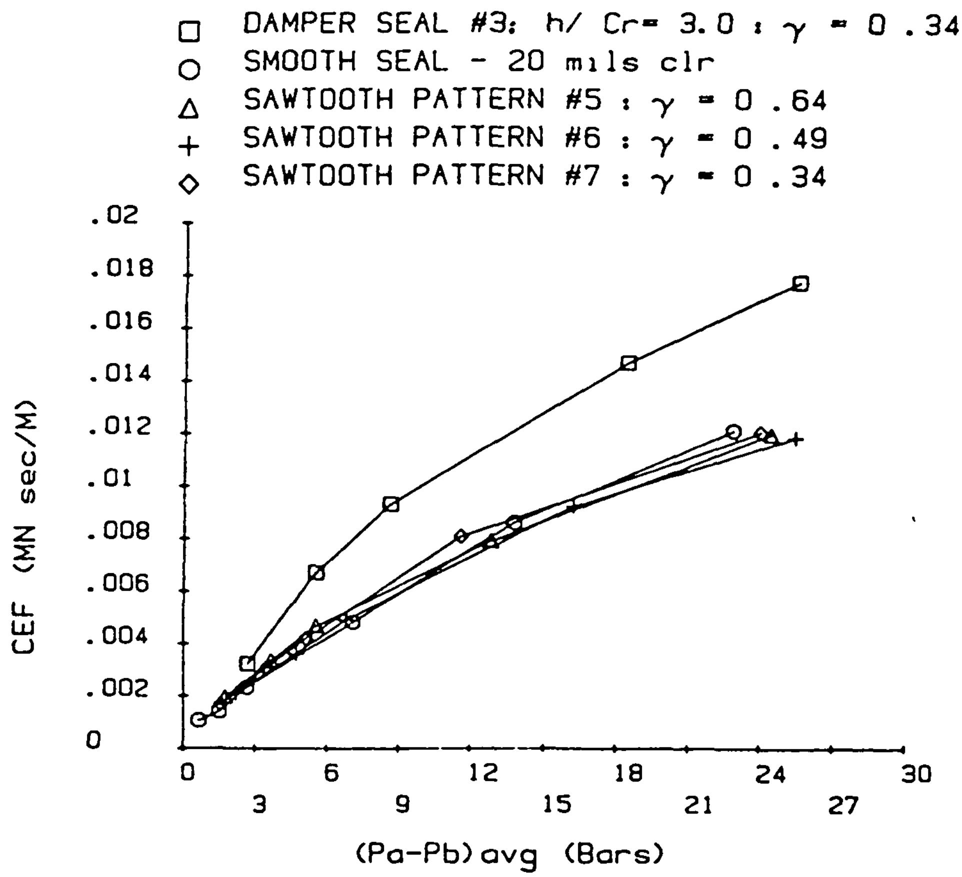


Figure 22. C_{ef} versus ΔP for sawtooth stators 5 through 7, a smooth stator, and the optimum-damping round-hole-pattern stator.

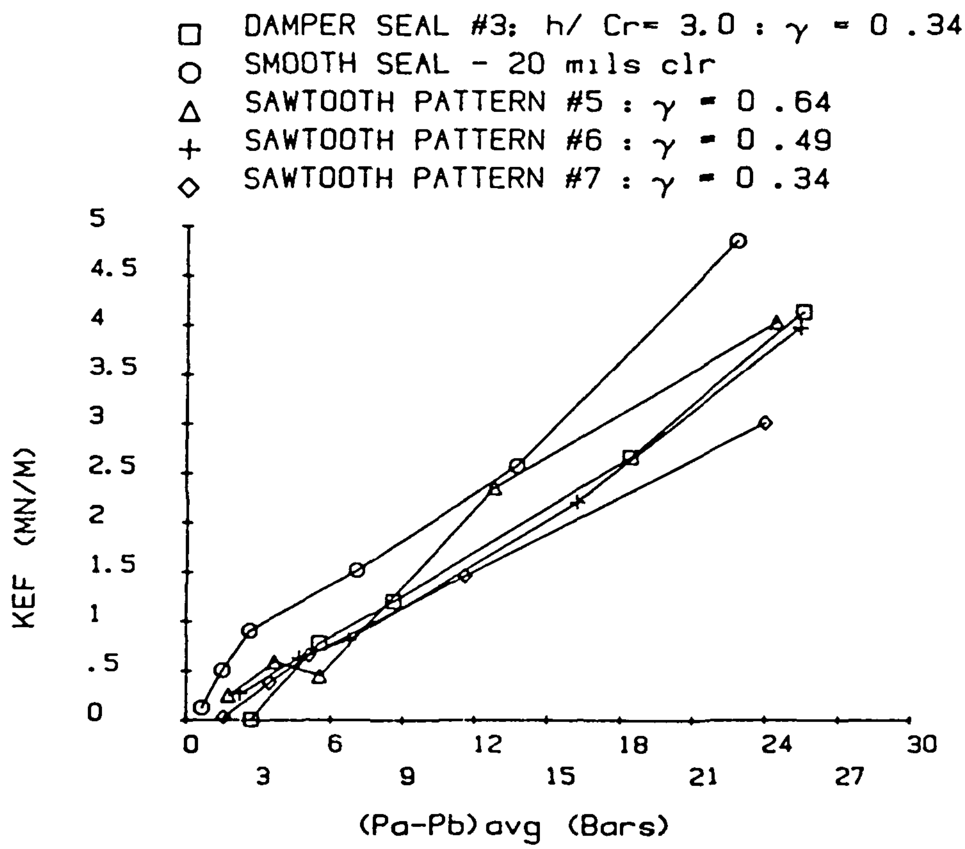


Figure 23. K_{ef} versus ΔP for sawtooth stators 5 through 7, a smooth stator, and the optimum-damping round-hole-pattern stator.

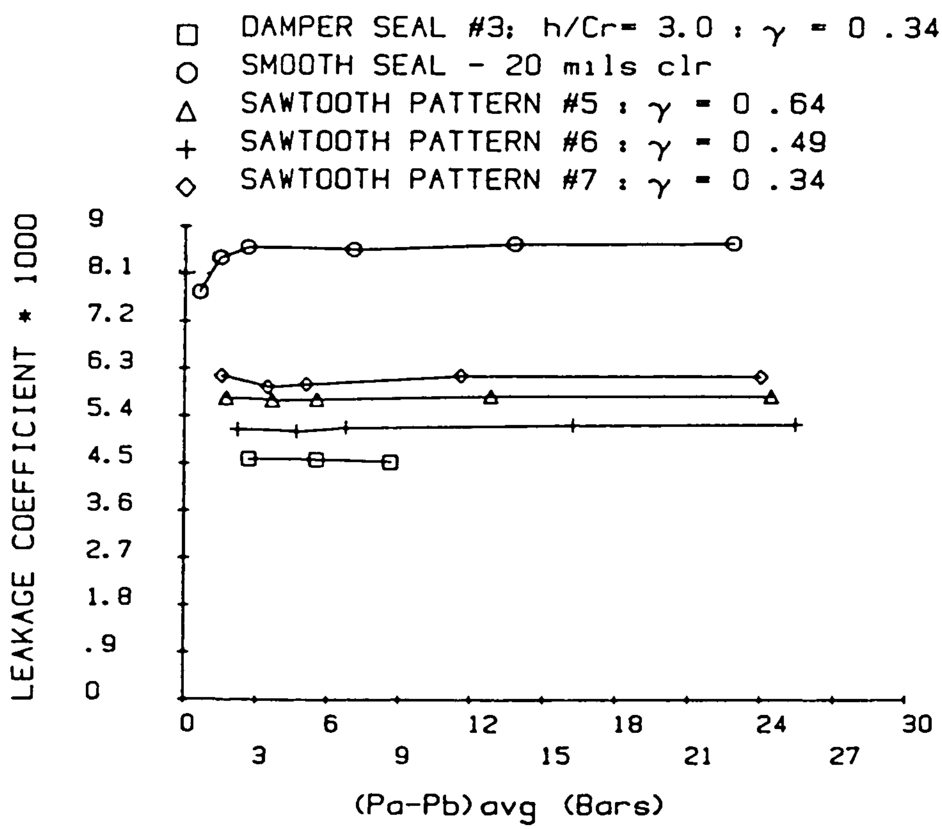


Figure 24. C_L versus ΔP for sawtooth stators 5 through 7, a smooth stator, and the optimum-damping round-hole-pattern stator.

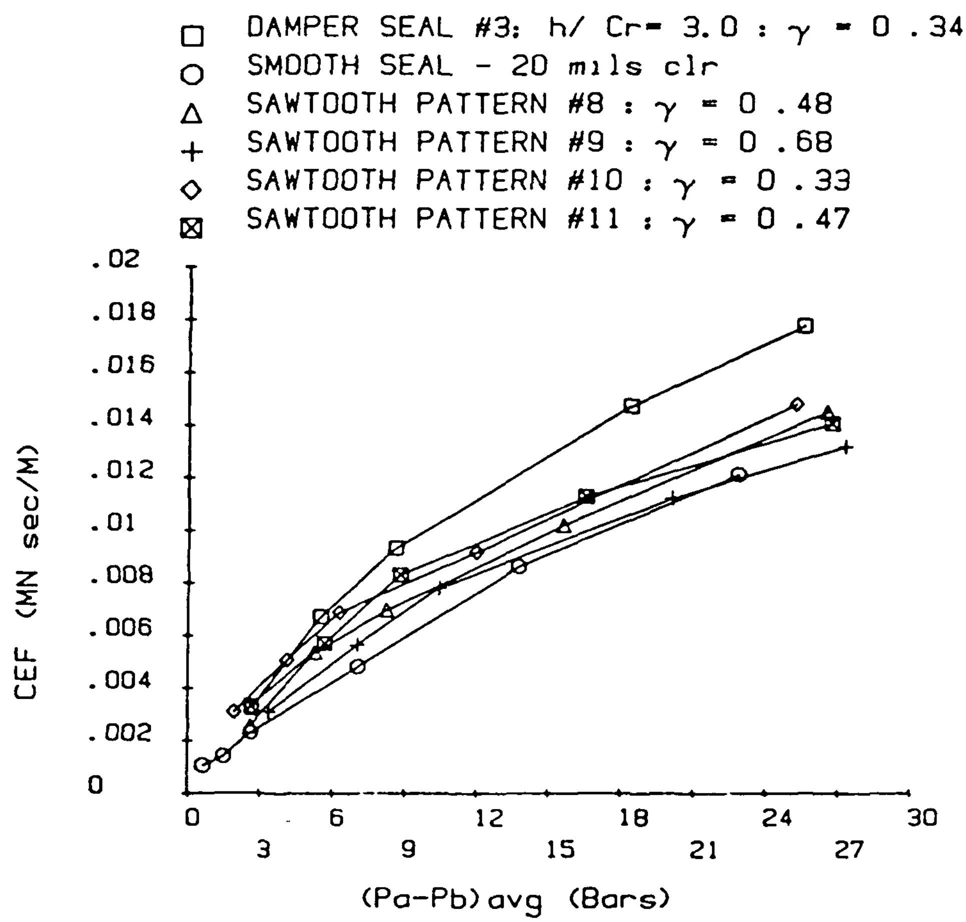


Figure 25. C_{ef} **versus** ΔP **for sawtooth stators 8 through 11, a smooth stator, and the optimum-damping round-hole-pattern stator.**

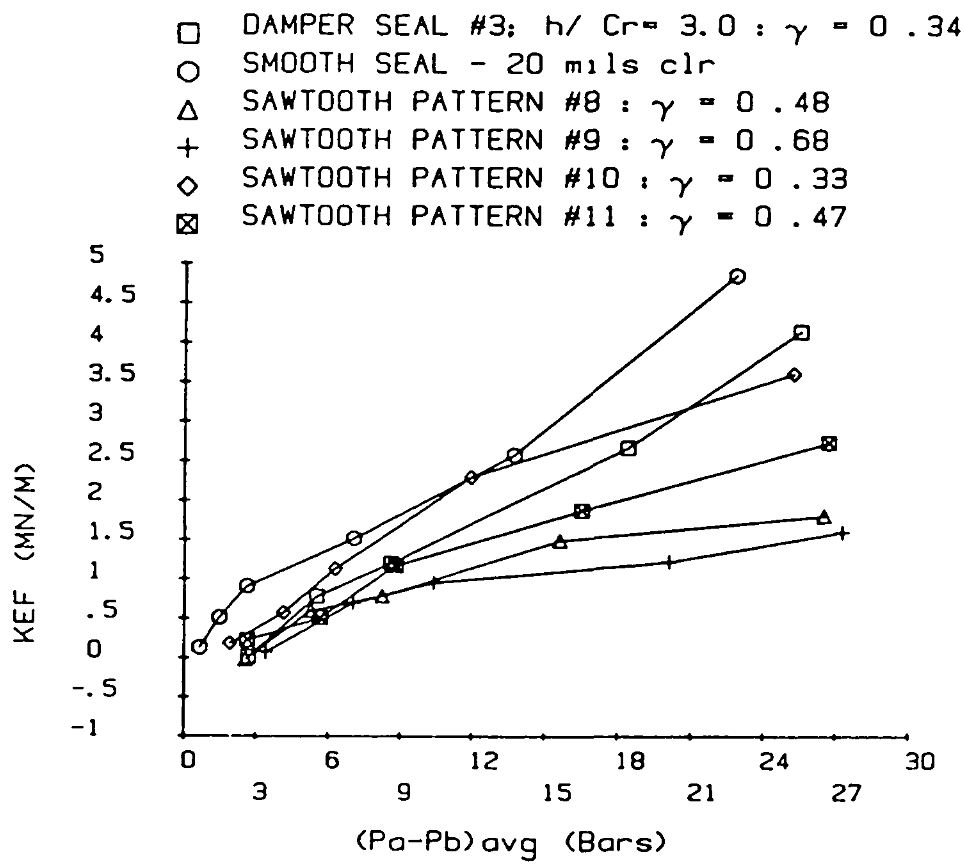


Figure 26. K_{ef} versus ΔP for sawtooth stators 8 through 11, a smooth stator, and the optimum-damping round-hole-pattern stator.

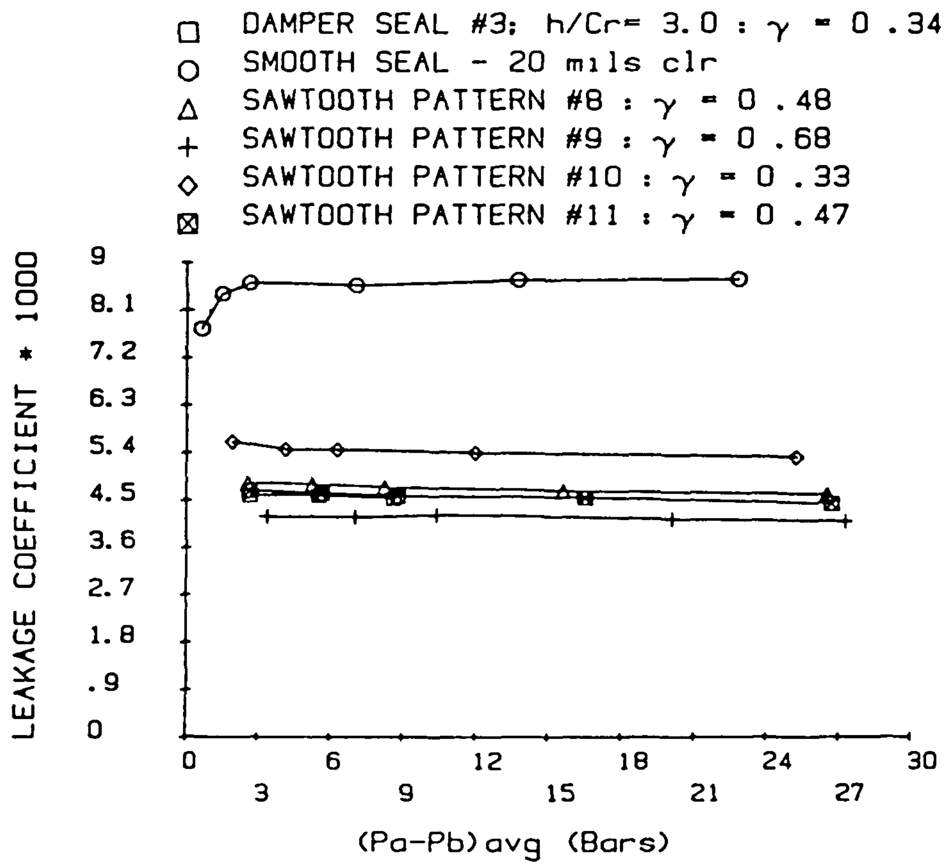


Figure 27. C_L versus ΔP for sawtooth stators 8 through 11, a smooth stator, and the optimum-damping round-hole-pattern stator.

Test results for stators 1 through 4 are presented in figures 19 through 21. Results for thee seals are grouped together, because they have the same groove geometry and $h/C_r = 5$. From figure 19, the damping performance of those seals is, at best, comparable to that of a smooth seal and substantially inferior to the best damper seal. As illustrated in figure 20, K_{ef} for these seals is generally less than comparable values for the damper seal and significantly less than measured values for a smooth seal. Stators 1 and 2 have perceptibly higher stiffness valves than stators 3 and 4, presumably because of differences in Υ for the two stator groups. Test results for hole-pattern seals [7] showed a consistent drop in K_{ef} as Υ increases. Figure 21 shows stators 1 through 4 to leak substantially less than a smooth seal. Stators 1 and 2 leak worse than the damper seal; seals 3 and 4 leak less. The original vortex flowmeters used for leakage measurements were replaced by turbine flowmeters between tests for stators 3 and 4, because they yielded invalid data at higher Reynolds numbers.

The results for sawtooth patterns 5 through 7 are grouped together in figures 22 through 25, because these stators have the same groove geometry, and all have $h/C_r = 2$. The sawtooth cross-section of stator number 5 coincides with the original axially-grooved seal of [6]. These seals differ only in the number of grooves used in the sawtooth cross section with a consequent change in the hole-density parameter Υ. Figure 22 shows the damping performance of these stators to be comparable to a smooth seal and substantially inferior to the best hole-pattern damper seal. The stiffness results of figure 23 are erratic but generally show stiffness values on a par with the damper seal. The leakage results of figure 25 show that all of these seals leak worse than the hole-pattern damper seal but less than a smooth seal.

The results for stators 8 through 11 are grouped together in figures 25 through 27 because they have the same groove geometry and all have $h/C_r = 3.0$. The design for these seals was guided by results for the hole-pattern seal which showed maximum damping to result for $h/C_r = 3.0$ and $\gamma = 0.34$. Figure 25 shows that all of these stators have better damping performance than a smooth seal and worse than the hole-pattern damper seal. Figure 26 shows lower K_{ef} values for stators 8, 9, and 11 than the damper seal, but higher or comparable values for stator 10. Figure 27 shows superior leakage performance for stator 9 (γ=0.68), lesser but comparable performance for stators 11 (γ=0.47) and 8 (γ=0.47), and the worst performance for stator 10 (γ=0.33). Stators 8 and 11 have about the same leakage performance as the hole-pattern stator. All of the sawtooth-pattern stators have much better performance than the smooth seal.

From an overall viewpoint the best <u>leakage performance</u> for a sawtooth pattern seal is provided by stators #9 (γ=0.68, h/C_r=3) and #3 or #4 (γ=0.74, h/C_r=5.0). The maximum effective <u>damping performance</u> is turned in by seals #8 (γ=0.48, h/C_r=3), #10 (γ=0.33, h/C_r=3), and #11 (γ=0.47, h/C_r=3); each of which provides a maximum at various ΔP values in figure 24. The <u>maximum</u> K_{ef} values are provided by seals #10 (γ=0.33, h/C_r=3) and #7 (γ=0.34, h/C_r=2).

These results support the following general conclusions:

(a) Leakage performance is improved by increasing γ and h/Cr. From table 1, the minimum-leakage stators used dams with thin widths (G=0.4775 mm). A comparison of the results for stators 3 and 4 or 1 and 2 in figure 20 shows no particular advantage for either straight or staggered assemblies.

(b) The clear superiority of the $h/C_r = 3$ ratio in maximizing C_{ef} is evident in the superior performances of stators 8, 10, and 11. The results do not seem to be particularly sensitive to γ.

(c) Stiffness is decreased by increasing h/C_r and γ.

From a rotordynamics viewpoint, stator number 10 has the best combined attributes of maximizing C_{ef} and K_{ef}. Interestingly, the parameters $\gamma = 0.33$ and $h/C_r = 3$ are almost exactly those obtained for the hole-pattern seal with maximum damping (γ=0.34, h/C_r=3). Note, however, from figures 27 that stator number 10 leaks substantially more than the hole-pattern damper seal.

CONCLUSIONS

The results of this test program support the following general conclusions:

(a) A sawtooth-pattern damper seal can be developed which has substantially better leakage and damping performance than a corresponding smooth seal; however, the best sawtooth-pattern seal tested in this program was substantially inferior to the best round-hole-pattern seal developed earlier, in terms of both net-damping coefficients and leakage.

(b) Leakage performance is improved by increasing γ and h/C_r. No advantage is demonstrated by using staggered versus inline assembly of sawtooth-pattern seal segments. Leakage performance is better with thin dams, which increases γ.

(c) For the h/C_r ratios tested (2, 3, 5), $h/C_r = 3$ is clearly superior.

(d) Stiffness is decreased by increasing h/C_r and γ.

(e) In terms of γ and h/C_r, the sawtooth pattern seal with the best rotordynamic performance in terms of the ordered criteria (i) maximum damping and (ii) maximum stiffness had $h/C_r = 3$, $\gamma = 0.33$. These are almost the same nondimensional parameters which were obtained for the maximum-damping round-hole-pattern seal ($h/C_r=3$, $\gamma=0.34$).

REFERENCES

1. von Pragenau, G. L., "Damping Seals for Turbomachinery," NASA Technical Paper 1987, 1982.

2. Childs, D. W. and Kim, C-H., "Analysis and Testing of Turbulent Annular Seals with Different, Directionally Homogeneous Surface Roughness Treatments for Rotor and Stator Elements," ASME Trans. Journal of Tribology Technology, July 1985, Vol. 107, pp. 296-306.

3. Childs, D. W., "SSME HPFTP Interstage Seals: Analysis and Experiments for Leakage and Reaction-Force Coefficients," Progress Report, NAS 8-33716, Texas A&M University-Turbomachinery Laboratories Report, Seal-1-83, 15 February 1983.

4. Childs., D. W., "SSME HPFTP Interstage Seals: Analysis and Experiments for Leakage and Reaction-Force Coefficients," Supplementary Progress Report, NASA Contract NAS8-33716, Texas A&M University-Turbomachinery Laboratories Report Seal-2-83, 15 July 1983.

5. Childs, D. W., "SSME Seal Program: Leakage Tests for Helically-Grooved Seals," Progress Report NASA Contract NAS8-33716, Texas A&M University, Turbomachinery Laboratories Report, Seal-3-83, November 1983.

6. Childs, D. W., "SSME Interstage Seal Research" Progress Report Contract NAS8-33716, Texas A&M University, Turbomachinery Laboratories Report, Seal-1-84, January 1984.

7. Childs, D. W., "SSME Seal Test Program: Test Results for Hole-Pattern Damper Seals" Interim Progress Report Contract NAS8-35824, Texas A&M University, Turbomachinery Laboratories Report, Seal-4-85, July 1985.

APPENDIX A.

STATIC TEST RESULTS FOR SAWTOOTH PATTERN STATORS

A.1 Test Data: Operating Conditions and Parameters for stator 1.

SAWTOOTH PATTERN #1
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.40
DR. D. CHILDS TEXAS A&M JUN 85

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	1.771	1562.614	.149E-03	2.117	1083.
2.	1.828	1567.144	.150E-03	2.143	1791.
3.	1.927	1567.426	.150E-03	2.142	2691.
4.	2.113	1574.624	.152E-03	2.172	3614.
5.	2.562	1574.333	.152E-03	2.160	5310.
6.	3.111	1553.664	.146E-03	2.105	7186.
7.	4.171	1568.656	.151E-03	3.111	1079.
8.	4.312	1578.434	.153E-03	3.140	1818.
9.	4.462	1583.100	.154E-03	3.183	2740.
10.	4.358	1572.572	.152E-03	3.117	3614.
11.	4.470	1564.637	.149E-03	3.079	5310.
12.	5.604	1554.211	.146E-03	3.000	7186.
13.	6.245	1554.485	.147E-03	3.719	1049.
14.	6.235	1555.251	.147E-03	3.702	1765.
15.	6.391	1560.830	.148E-03	3.765	2661.
16.	6.376	1558.448	.148E-03	3.754	3529.
17.	6.603	1556.750	.147E-03	3.743	5310.
18.	7.200	1549.492	.145E-03	3.699	7186.
19.	15.662	1565.627	.149E-03	6.115*	1079.
20.	15.638	1564.261	.149E-03	6.108*	1780.
21.	15.660	1561.005	.148E-03	6.105*	2661.
22.	15.675	1566.064	.149E-03	6.118*	3571.

23.	15.632	1568.528	.150E-03	6.115*	5310.
24.	16.015	1550.847	.145E-03	6.154*	7186.
25.	24.511	1538.901	.142E-03	7.436	1020.
26.	24.606	1539.694	.142E-03	7.429	1724.
27.	24.575	1541.781	.142E-03	7.492	2586.
28.	24.773	1545.763	.143E-03	7.482	3468.
29.	24.948	1546.871	.144E-03	7.459	5310.
30.	25.074	1555.547	.146E-03	7.070	7186.

* ESTIMATED

A.2 Test Data: Operating Conditions and Parameters for stator 2 .

SAWTOOTH PATTERN #2
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.40
DR. D. CHILDS   TEXAS A&M   JUN 85

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (kg/sec)	CPM (Cyc/min)
1.	1.852	1572.581	.151E-03	2.148	1083.
2.	1.872	1568.366	.150E-03	2.141	1796.
3.	1.915	1567.302	.150E-03	2.135	2685.
4.	1.992	1564.127	.149E-03	2.132	3561.
5.	2.517	1560.065	.148E-03	2.104	5333.
6.	3.208	1559.566	.148E-03	2.123	7186.
7.	4.067	1570.826	.151E-03	3.123	1083.
8.	4.058	1569.996	.151E-03	3.098	1796.
9.	4.136	1571.408	.151E-03	3.109	2697.
10.	4.157	1571.966	.151E-03	3.111	3593.
11.	4.339	1559.469	.148E-03	3.048	5333.
12.	5.571	1560.343	.148E-03	3.059	7186.
13.	5.852	1559.464	.148E-03	3.749	1071.
14.	6.097	1566.893	.150E-03	3.785	1791.
15.	6.169	1564.223	.149E-03	3.773	2673.
16.	3.944	1555.661	.147E-03	3.017	3529.
17.	6.284	1556.726	.147E-03	3.721	5333.
18.	7.281	1554.951	.147E-03	3.711	7229.
19.	15.301	1563.062	.149E-03	6.039*	1068.
20.	15.295	1562.493	.148E-03	6.036*	1780.
21.	15.292	1559.358	.148E-03	6.030*	2661.
22.	15.327	1557.727	.147E-03	6.034*	3529.

23.	15.314	1555.988	.147E-03	6.027*	5333.
24.	15.276	1549.171	.145E-03	6.007*	7186.
25.	24.453	1546.736	.144E-03	7.612	1038.
26.	24.550	1554.389	.146E-03	7.640	1749.
27.	24.553	1554.342	.146E-03	7.605	2626.
28.	24.610	1548.028	.144E-03	7.522	3458.
29.	24.768	1551.430	.145E-03	7.542	5333.
30.	24.896	1548.561	.144E-03	7.063	7186.

* ESTIMATED

A.3 Test Data: Operating Conditions and Parameters for stator 3.

SAWTOOTH PATTERN #3
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=.74
DR. D. CHILDS TEXAS A&M JUL 85

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	3.302	1571.601	.151E-03	2.168	1083.
2.	3.272	1564.658	.149E-03	2.143	1786.
3.	3.347	1563.036	.149E-03	2.135	2679.
4.	3.534	1571.633	.151E-03	2.155	3604.
5.	3.820	1571.961	.151E-03	2.161	5333.
6.	3.905	1548.476	.145E-03	2.084	7186.
7.	7.219	1581.941	.154E-03	3.182	1079.
8.	7.279	1581.071	.154E-03	3.162	1818.
9.	7.365	1582.264	.154E-03	3.171	2733.
10.	7.228	1570.718	.151E-03	3.128	3593.
11.	7.680	1573.583	.152E-03	3.116	5333.
12.	8.303	1559.061	.148E-03	3.047	7186.
13.	10.618	1575.780	.152E-03	3.861	1071.
14.	10.665	1577.425	.153E-03	3.880	1802.
15.	10.088	1563.663	.149E-03	3.768	2673.
16.	10.427	1565.158	.149E-03	3.788	3571.
17.	10.659	1564.231	.149E-03	3.782	5333.
18.	11.234	1551.642	.146E-03	3.710	7186.
19.	18.378	1564.530	.149E-03	5.044*	1064.
20.	18.389	1564.043	.149E-03	5.044*	1770.
21.	18.395	1571.861	.151E-03	5.056*	2691.
22.	18.385	1563.803	.149E-03	5.043*	3550.

23.	18.353	1557.125	.147E-03	5.028*	5333.
24.	18.396	1554.498	.146E-03	5.030*	7186.
25.	26.753	1542.890	.143E-03	6.043*	1031.
26.	26.993	1552.170	.145E-03	6.088*	1749.
27.	27.012	1555.346	.146E-03	6.095*	2632.
28.	27.080	1553.727	.145E-03	6.101*	3509.
29.	27.249	1555.145	.146E-03	6.123*	5310.
30.	27.062	1541.786	.142E-03	6.075*	7186.

* ESTIMATED

A.4 Test Data: Operating Conditions and Parameters for stator 4.

SAWTOOTH PATTERN #4
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=.74
DR. D. CHILDS TEXAS A&M AUG 1985

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	2.647	1559.595	.148E-03	2.125	1060.
2.	2.752	1558.975	.148E-03	2.121	1775.
3.	2.810	1561.488	.149E-03	2.114	2673.
4.	2.852	1559.899	.148E-03	2.106	3550.
5.	3.053	1563.428	.149E-03	2.124	5333.
6.	3.614	1572.061	.151E-03	2.148	7186.
7.	6.213	1569.641	.151E-03	3.105	1071.
8.	6.276	1566.237	.150E-03	3.097	1791.
9.	6.318	1562.409	.149E-03	3.049	2673.
10.	6.494	1563.464	.149E-03	3.088	3571.
11.	6.714	1566.980	.150E-03	3.085	5333.
12.	6.839	1577.190	.153E-03	3.133	7186.
13.	10.369	1558.714	.148E-03	3.754	1075.
14.	10.433	1559.318	.148E-03	3.760	1775.
15.	10.067	1572.338	.151E-03	3.830	2703.
16.	10.275	1570.426	.151E-03	3.826	3593.
17.	10.093	1563.946	.149E-03	3.782	5333.
18.	10.240	1571.519	.151E-03	3.817	7229.
19.	16.949	1564.816	.149E-03	4.947	1068.
20.	17.247	1568.887	.150E-03	4.997	1791.
21.	17.250	1569.980	.150E-03	4.991	2691.
22.	17.710	1575.003	.152E-03	5.045	3604.

23.	17.652	1566.129	.149E-03	4.956	5310.
24.	18.203	1575.369	.152E-03	5.053	7186.
25.	26.834	1566.028	.149E-03	6.202	1068.
26.	26.897	1570.947	.150E-03	6.237	1786.
27.	26.896	1567.587	.149E-03	6.244	2661.
28.	27.063	1572.229	.150E-03	6.266	3571.
29.	27.171	1568.518	.149E-03	6.190	5310.
30.	26.955	1563.590	.148E-03	6.106	7186.

A.5 Test Data: Operating Conditions and Parameters for stator 5.

SAWTOOTH PATTERN #5
105 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.64
DR. D. CHILDS TEXAS A&M SEPT. 1985

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	1.413	1562.525	.149E-03	2.116	1075.
2.	1.483	1563.524	.149E-03	2.118	1786.
3.	1.530	1560.395	.148E-03	2.103	2661.
4.	1.785	1563.322	.149E-03	2.140	3571.
5.	1.982	1568.470	.150E-03	2.145	5333.
6.	2.295	1560.477	.148E-03	2.126	7186.
7.	3.360	1566.388	.150E-03	3.091	1068.
8.	3.401	1565.177	.150E-03	3.088	1786.
9.	3.478	1567.863	.150E-03	3.082	2691.
10.	3.642	1567.167	.150E-03	3.094	3571.
11.	4.161	1571.505	.151E-03	3.124	5333.
12.	4.044	1561.680	.149E-03	3.058	7186.
13.	5.213	1569.004	.151E-03	3.801	1083.
14.	5.280	1569.590	.151E-03	3.816	1796.
15.	5.451	1572.859	.152E-03	3.839	2709.
16.	5.215	1561.992	.149E-03	3.771	3561.
17.	6.002	1576.996	.153E-03	3.862	5310.
18.	6.144	1562.043	.149E-03	3.776	7186.
19.	12.713	1561.198	.148E-03	5.862	1060.
20.	12.698	1560.015	.148E-03	5.861	1760.
21.	12.597	1558.494	.147E-03	5.848	2661.
22.	12.764	1556.633	.147E-03	5.836	3529.

23.	13.267	1565.484	.149E-03	5.912	5310.
24.	12.819	1546.424	.144E-03	5.720	7186.
25.	24.447	1569.998	.150E-03	8.107	1083.
26.	24.433	1570.538	.150E-03	8.110	1780.
27.	24.467	1570.264	.150E-03	8.103	2679.
28.	24.357	1558.141	.147E-03	8.087	3509.
29.	24.520	1564.331	.148E-03	8.103	5286.
30.	24.409	1556.987	.146E-03	8.023	7186.

A.6 Test Data: Operating Conditions and Parameters for stator 6.

SAWTOOTH PATTERN #6
80 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.49
DR. D. CHILDS TEXAS A&M SEPT. 1985

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	1.823	1570.768	.151E-03	2.151	1075.
2.	1.904	1567.019	.150E-03	2.129	1780.
3.	2.035	1567.306	.150E-03	2.139	2667.
4.	2.226	1562.222	.149E-03	2.131	3561.
5.	2.424	1561.609	.149E-03	2.128	5310.
6.	2.748	1577.118	.153E-03	2.189	7186.
7.	4.199	1568.189	.150E-03	3.089	1060.
8.	4.388	1576.474	.152E-03	3.130	1802.
9.	4.604	1582.802	.154E-03	3.177	2740.
10.	4.721	1585.451	.155E-03	3.195	3659.
11.	5.155	1581.084	.154E-03	3.176	5310.
12.	5.057	1558.649	.148E-03	3.039	7186.
13.	6.699	1584.808	.155E-03	3.927	1095.
14.	6.275	1568.556	.150E-03	3.799	1796.
15.	6.459	1566.266	.150E-03	3.788	2685.
16.	6.559	1565.866	.150E-03	3.786	3571.
17.	6.884	1560.934	.148E-03	3.750	5286.
18.	7.680	1568.370	.150E-03	3.801	7186.
19.	15.864	1566.193	.149E-03	5.912	1064.
20.	16.389	1579.019	.153E-03	6.037	1813.
21.	15.808	1568.177	.150E-03	5.937	2685.
22.	15.981	1571.689	.151E-03	5.961	3582.

23.	16.396	1573.099	.151E-03	5.994	5286.
24.	16.718	1568.968	.150E-03	5.950	7186.
25.	25.387	1565.117	.148E-03	7.503	1075.
26.	25.380	1564.744	.148E-03	7.481	1765.
27.	25.376	1563.568	.148E-03	7.461	2661.
28.	25.491	1568.974	.149E-03	7.524	3561.
29.	25.591	1567.884	.149E-03	7.507	5286.
30.	25.294	1544.496	.143E-03	7.392	7186.

A.7 Test Data: Operating Conditions and Parameters for stator 7.

SAWTOOTH PATTERN #7
55 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.34
DR. D. CHILDS TEXAS A&M SEPT 1985

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	1.163	1552.776	.146E-03	2.089	1049.
2.	1.191	1556.328	.147E-03	2.096	1760.
3.	1.264	1556.421	.147E-03	2.093	2655.
4.	1.656	1577.213	.153E-03	2.185	3614.
5.	1.858	1567.952	.150E-03	2.138	5310.
6.	2.124	1577.499	.153E-03	2.166	7186.
7.	3.156	1580.274	.154E-03	3.158	1103.
8.	3.197	1579.891	.153E-03	3.156	1818.
9.	3.263	1574.740	.152E-03	3.121	2703.
10.	3.472	1582.988	.154E-03	3.162	3647.
11.	3.841	1578.865	.153E-03	3.163	5310.
12.	3.914	1572.686	.151E-03	3.122	7186.
13.	4.914	1579.846	.153E-03	3.897	1079.
14.	4.893	1578.396	.153E-03	3.874	1807.
15.	4.864	1572.490	.151E-03	3.837	2697.
16.	5.027	1575.250	.152E-03	3.847	3604.
17.	5.231	1567.119	.150E-03	3.793	5333.
18.	5.630	1567.713	.150E-03	3.799	7186.
19.	10.857	1560.114	.148E-03	5.850	1068.
20.	11.429	1572.582	.151E-03	5.980	1786.
21.	11.564	1575.129	.152E-03	5.993	2697.
22.	11.624	1574.787	.152E-03	5.995	3604.

23.	11.749	1565.512	.149E-03	5.909	5310.
24.	12.184	1563.852	.149E-03	5.900	7186.
25.	24.050	1570.502	.150E-03	8.549	1060.
26.	24.081	1572.648	.150E-03	8.571	1796.
27.	23.749	1553.462	.145E-03	8.487	2614.
28.	23.796	1568.311	.149E-03	8.526	3550.
29.	24.117	1567.635	.149E-03	8.523	5333.
30.	24.150	1566.071	.149E-03	8.497	7186.

A.8 Test Data: Operating Conditions and Parameters for stator 8.

SAWTOOTH PATTERN #8
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.48
DR. D. CHILDS TAMU NOV 1985

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	3.020	1599.186	.159E-03	2.270	1099.
2.	2.534	1583.923	.155E-03	2.208	1835.
3.	2.111	1568.212	.150E-03	2.134	2685.
4.	2.513	1585.350	.155E-03	2.215	3670.
5.	2.637	1584.438	.155E-03	2.194	5310.
6.	2.676	1571.742	.151E-03	2.163	7186.
7.	5.650	1569.324	.151E-03	3.095	1064.
8.	5.843	1590.980	.156E-03	3.215	1840.
9.	5.132	1572.798	.152E-03	3.124	2697.
10.	4.757	1567.061	.150E-03	3.089	3571.
11.	5.056	1570.674	.151E-03	3.094	5310.
12.	5.243	1564.195	.149E-03	3.072	7229.
13.	8.870	1575.488	.152E-03	3.847	1071.
14.	8.567	1572.338	.151E-03	3.833	1802.
15.	8.008	1569.128	.150E-03	3.817	2685.
16.	8.170	1588.052	.155E-03	3.929	3659.
17.	7.744	1584.869	.155E-03	3.904	5310.
18.	8.178	1574.030	.152E-03	3.837	7186.
19.	16.907	1565.687	.149E-03	5.193	1075.
20.	16.964	1576.956	.152E-03	5.294	1796.
21.	16.475	1575.028	.152E-03	5.292	2697.
22.	15.197	1562.464	.148E-03	5.159	3540.

23.	14.490	1562.672	.148E-03	5.181	5310.
24.	13.661	1559.015	.147E-03	5.123	7186.
25.	26.674	1568.874	.149E-03	6.512	1079.
26.	26.685	1578.748	.152E-03	6.598	1807.
27.	26.532	1572.455	.150E-03	6.634	2691.
28.	26.474	1571.205	.150E-03	6.723	3582.
29.	26.434	1572.594	.150E-03	6.855	5310.
30.	26.453	1572.719	.150E-03	7.023	7186.

A.9 Test Data: Operating Conditions and Parameters for stator 9.

SAWTOOTH PATTERN #9
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.68
DR. D. CHILDS TAMU NOV 1985

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	3.457	1577.099	.153E-03	2.177	1075.
2.	3.470	1582.873	.154E-03	2.207	1813.
3.	3.177	1572.945	.152E-03	2.156	2697.
4.	3.215	1581.445	.154E-03	2.197	3636.
5.	3.410	1575.095	.152E-03	2.181	5286.
6.	3.588	1579.434	.153E-03	2.173	7186.
7.	7.311	1568.534	.150E-03	3.099	1064.
8.	7.440	1583.330	.154E-03	3.166	1813.
9.	6.942	1570.156	.151E-03	3.092	2691.
10.	6.863	1573.601	.152E-03	3.130	3604.
11.	6.643	1574.706	.152E-03	3.133	5286.
12.	7.011	1586.952	.155E-03	3.201	7186.
13.	10.873	1572.766	.151E-03	3.844	1087.
14.	10.773	1573.605	.151E-03	3.847	1796.
15.	10.909	1584.866	.154E-03	3.912	2721.
16.	10.355	1575.000	.152E-03	3.851	3604.
17.	9.754	1574.462	.152E-03	3.839	5310.
18.	9.726	1567.747	.150E-03	3.813	7186.
19.	20.453	1567.058	.150E-03	5.204	1068.
20.	21.021	1574.662	.151E-03	5.282	1796.
21.	20.341	1570.219	.150E-03	5.232	2679.
22.	19.875	1566.976	.149E-03	5.207	3571.

23.	19.496	1567.761	.150E-03	5.206	5310.
24.	19.376	1577.144	.152E-03	5.299	7186.
25.	27.362	1581.385	.153E-03	5.995	1099.
26.	27.236	1580.554	.153E-03	6.007	1796.
27.	27.357	1582.275	.153E-03	6.031	2709.
28.	27.321	1579.437	.152E-03	6.050	3604.
29.	27.167	1571.607	.150E-03	6.111	5310.
30.	27.195	1573.499	.151E-03	6.200	7186.

A.10 Test Data: Operating Conditions and Parameters for stator 10.

SAWTOOTH PATTERN #10
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.33
DR. D. CHILDS TAMU DEC 1985

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (kg/sec)	CPM (Cyc/min)
1.	1.795	1577.146	.153E-03	2.187	1079.
2.	1.586	1574.867	.152E-03	2.175	1807.
3.	1.602	1575.862	.152E-03	2.168	2721.
4.	1.621	1566.832	.150E-03	2.138	3571.
5.	2.204	1578.751	.153E-03	2.175	5333.
6.	2.711	1580.005	.153E-03	2.187	7186.
7.	4.146	1577.064	.153E-03	3.141	1087.
8.	4.000	1577.241	.153E-03	3.136	1796.
9.	3.700	1572.719	.151E-03	3.111	2691.
10.	3.803	1584.394	.155E-03	3.173	3636.
11.	4.319	1581.356	.154E-03	3.161	5333.
12.	4.849	1576.759	.153E-03	3.140	7186.
13.	6.831	1587.446	.155E-03	3.942	1095.
14.	6.120	1571.350	.151E-03	3.826	1802.
15.	6.253	1587.240	.155E-03	3.929	2752.
16.	5.830	1571.014	.151E-03	3.829	3593.
17.	6.032	1584.656	.155E-03	3.914	5310.
18.	6.663	1569.947	.151E-03	3.828	7186.
19.	12.789	1576.233	.152E-03	5.288	1071.
20.	12.766	1582.442	.154E-03	5.348	1813.
21.	12.476	1584.178	.154E-03	5.367	2727.
22.	11.979	1578.669	.153E-03	5.317	3614.

23.	11.135	1570.151	.151E-03	5.238	5310.
24.	10.682	1562.551	.148E-03	5.166	7186.
25.	25.429	1575.180	.151E-03	7.446	1095.
26.	25.195	1569.815	.150E-03	7.424	1775.
27.	25.240	1577.859	.152E-03	7.530	2709.
28.	25.297	1576.074	.151E-03	7.566	3593.
29.	25.219	1574.225	.151E-03	7.656	5310.
30.	25.163	1575.861	.151E-03	7.808	7186.

A.11 Test Data: Operating Conditions and Parameters for stator 11.

SAWTOOTH PATTERN #11
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.47
DR. D. CHILDS TAMU JAN 1986

Case	Pa-Pb (Bars)	RHO (Kg/M)	MU (N sec/M)	MDOT (Kg/sec)	CPM (Cyc/min)
1.	2.451	1563.701	.149E-03	2.128	1060.
2.	2.521	1576.753	.153E-03	2.172	1796.
3.	2.269	1571.782	.151E-03	2.147	2685.
4.	2.569	1575.264	.152E-03	2.175	3604.
5.	2.894	1562.399	.149E-03	2.124	5357.
6.	3.137	1555.878	.147E-03	2.092	7186.
7.	5.982	1574.743	.152E-03	3.117	1091.
8.	5.778	1570.615	.151E-03	3.117	1791.
9.	5.587	1578.406	.153E-03	3.156	2721.
10.	5.074	1572.226	.151E-03	3.111	3593.
11.	5.448	1566.074	.150E-03	3.081	5333.
12.	6.110	1568.835	.150E-03	3.092	7229.
13.	9.321	1572.893	.151E-03	3.824	1083.
14.	9.383	1581.614	.154E-03	3.899	1807.
15.	9.153	1581.115	.153E-03	3.887	2721.
16.	8.594	1575.563	.152E-03	3.849	3604.
17.	7.989	1569.818	.151E-03	3.827	5333.
18.	8.319	1557.770	.147E-03	3.722	7186.
19.	17.675	1567.672	.150E-03	5.206	1071.
20.	17.422	1568.097	.150E-03	5.227	1770.
21.	17.594	1576.492	.152E-03	5.296	2709.
22.	16.438	1562.883	.148E-03	5.184	3561.

23.	15.640	1566.693	.149E-03	5.199	5333.
24.	14.422	1557.345	.147E-03	5.134	7229.
25.	26.743	1567.444	.149E-03	6.337	1075.
26.	26.857	1574.755	.151E-03	6.364	1796.
27.	26.503	1571.969	.150E-03	6.423	2685.
28.	26.932	1575.040	.151E-03	6.487	3582.
29.	26.824	1574.372	.151E-03	6.545	5333.
30.	26.446	1573.030	.151E-03	6.747	7186.

APPENDIX B.

DYNAMIC TEST DATA

FOR SAWTOOTH-PATTERN

B.1 Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 1.

SAWTOOTH PATTERN #1
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.40
DR. D. CHILDS TEXAS A&M JUN 85

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (KN)
1.	89805.	1083.	-.2448	.1044	.4490	.0529	.0665
2.	90169.	1791.	-.2212	.1051	.7681	.0697	.1024
3.	90078.	2691.	.0093	.0493	1.0124	.0516	.1287
4.	90209.	3614.	.1494	.0650	1.1853	.0544	.1520
5.	89791.	5310.	.9147	.0806	1.7644	.0792	.2527
6.	90754.	7186.	1.5592	.0926	1.8635	.1033	.3089
7.	130501.	1079.	-.4867	.0973	.6244	.1592	.1026
8.	129560.	1818.	-.4276	.0501	1.0543	.0636	.1447
9.	130314.	2740.	-.1675	.1035	1.6032	.0685	.2051
10.	129911.	3614.	-.2098	.0967	1.9245	.0828	.2462
11.	130125.	5310.	.7649	.1048	2.5085	.0898	.3334
12.	129369.	7186.	1.6878	.1419	3.2771	.1025	.4686
13.	160252.	1049.	-.6790	.1516	.8154	.1654	.1370
14.	159272.	1765.	-.6958	.1197	1.3235	.1038	.1904
15.	160314.	2661.	-.5049	.1030	1.9019	.1889	.2500
16.	160500.	3529.	-.5190	.1147	2.5125	.0973	.3261
17.	160508.	5310.	.5213	.1513	3.0896	.1277	.3984
18.	160863.	7186.	1.5855	.1527	4.0493	.1094	.5526
19.	258330.*	1079.	-1.7324	.1998	1.2310	.3870	.2750
20.	258250.*	1780.	-1.8909	.1371	2.3353	.1630	.3821
21.	256932.*	2661.	-1.6000	.0718	2.9058	.1449	.4213
22.	258375.*	3571.	-1.4506	.2452	3.9618	.1420	.5366

23.	259583.*	5310.	.1003	.1757	4.8994	.2011	.6227
24.	255414.*	7186.	.9832	.2682	6.8414	.1884	.8786
25.	331780.	1020.	-2.8467	.2611	1.3522	.6611	.4095
26.	330778.	1724.	-2.6993	.3117	2.2597	.1647	.4486
27.	332311.	2586.	-2.3082	.1259	3.4666	.3383	.5301
28.	329595.	3468.	-2.0976	.2624	4.5248	.3412	.6345
29.	327921.	5310.	-.6433	.3425	6.7066	.2952	.8569
30.	306051.	7186.	.9151	.3839	9.0915	.3254	1.1616

* ESTIMATED

B.2 Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 2.

SAWTOOTH PATTERN #2
25 TEETH, TOOTH DEPTH= 2.54mm, GAMMA=.40
DR. D. CHILDS TEXAS A&M JUN 85

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (kN)
1.	89548.	1083.	-.3414	.0813	.4149	.1022	.0700
2.	89921.	1796.	-.1281	.0574	.8134	.1207	.1048
3.	89800.	2685.	-.0373	.0814	.9555	.0776	.1218
4.	90163.	3561.	-.0776	.0910	1.1186	.1030	.1428
5.	89617.	5333.	.7436	.0905	1.8686	.0700	.2557
6.	90531.	7186.	1.7431	.2114	2.1500	.1034	.3522
7.	130509.	1083.	-.6936	.1197	.5795	.1380	.1167
8.	129673.	1796.	-.6202	.1139	.9721	.0753	.1469
9.	129815.	2697.	-.3722	.0390	1.4295	.0675	.1876
10.	129854.	3593.	-.3611	.0572	1.8167	.0663	.2354
11.	129975.	5333.	.5797	.0899	2.3990	.0767	.3137
12.	130246.	7186.	1.9833	.2625	3.4890	.1592	.5105
13.	160048.	1071.	-.8378	.1242	.6518	.1419	.1366
14.	159542.	1791.	-1.0063	.0566	1.2021	.1188	.1994
15.	159750.	2673.	-.5890	.1461	1.8011	.0795	.2414
16.	129583.	3529.	-.4844	.0498	1.9763	.0630	.2585
17.	159668.	5333.	.3460	.1256	3.0979	.1281	.3962
18.	159823.	7229.	1.6864	.2483	4.0689	.1780	.5606
19.	255528.*	1068.	-2.1022	.2778	.9059	.5454	.3004
20.	253785.*	1780.	-2.1409	.1589	2.1335	.1265	.3844
21.	254036.*	2661.	-2.0339	.1270	2.7720	.1268	.4370
22.	252762.*	3529.	-2.0064	.0844	4.0235	.1189	.5711

23.	252745.*	5333.	-.4235	.1789	5.2784	.1588	.6730
24.	249583.*	7186.	.6015	.3053	6.6945	.2704	.8546
25.	334598.	1038.	-3.4510	.4099	.8165	.8218	.4645
26.	331329.	1749.	-3.3722	.2139	2.2343	.3152	.5145
27.	329779.	2626.	-2.9444	.2103	3.6280	.2196	.5939
28.	330050.	3458.	-3.0300	.2133	4.9250	.3122	.7347
29.	328733.	5333.	-1.4692	.3093	6.8117	.3007	.8860
30.	309540.	7186.	.1576	.4329	9.4265	.3712	1.1988

* ESTIMATED

B.3 **Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 3.**

SAWTOOTH PATTERN #3
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.74
DR. D. CHILDS TEXAS A&M JUL 85

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	!F! (KN)
1.	90463.	1083.	-.0933	.1246	.5255	.0415	.0697
2.	90533.	1786.	-.0354	.0682	.9721	.0464	.1238
3.	90457.	2679.	.2399	.0880	1.4888	.1010	.1919
4.	89915.	3604.	.2854	.0918	1.9043	.0856	.2449
5.	90071.	5333.	1.2134	.1200	2.3630	.0910	.3378
6.	90610.	7186.	1.9311	.2163	1.8010	.1599	.3359
7.	130352.	1079.	-.2947	.1606	.7045	.1258	.0999
8.	129747.	1818.	-.1183	.1007	1.3789	.0701	.1762
9.	129836.	2733.	.3349	.1032	2.2448	.1723	.2883
10.	130641.	3593.	.7144	.0893	2.8247	.1040	.3702
11.	129477.	5333.	1.3838	.1777	4.0861	.1051	.5485
12.	130073.	7186.	2.5423	.2939	4.6886	.1826	.6784
13.	160170.	1071.	-.3716	.1668	.8452	.1220	.1196
14.	160523.	1802.	-.4130	.1504	1.6263	.0841	.2140
15.	159670.	2673.	.2860	.1015	2.2265	.2118	.2854
16.	160051.	3571.	.7262	.1384	3.3371	.1404	.4341
17.	160025.	5333.	1.5924	.1731	4.7144	.1221	.6326
18.	160680.	7186.	2.7514	.2875	5.9942	.2635	.8383
19.	207509.*	1064.	-.9253	.2826	.9843	.2380	.1773
20.	206466.*	1770.	-.9426	.1349	2.1424	.1730	.2977
21.	209855.*	2691.	.0717	.1974	2.5979	.1364	.3310
22.	207494.*	3550.	.2250	.2657	4.0082	.2089	.5110

23.	204979.*	5333.	1.9454	.2581	6.2690	.2243	.8346
24.	204067.*	7186.	3.1251	.3990	7.6711	.2897	1.0534
25.	242003.*	1031.	-1.2208	.3241	.8348	.2228	.1929
26.	245605.*	1749.	-1.3699	.2138	2.1724	.1538	.3274
27.	247074.*	2632.	-.6109	.1846	3.2563	.1845	.4216
28.	245880.*	3509.	.1301	.1489	4.7979	.1774	.6099
29.	248256.*	5310.	2.1437	.2507	7.2223	.2108	.9573
30.	241631.*	7186.	3.9646	.4594	9.8708	.5116	1.3523

* ESTIMATED

B.4 Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 4.

SAWTOOTH PATTERN #4
25 TEETH, TOOTH DEPTH= 2.540mm, GAMMA=0.74
DR. D. CHILDS TEXAS A&M AUG 1985

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (KN)
1.	90618.	1060.	-.0568	.1094	.4415	.0696	.0581
2.	90530.	1775.	.0567	.0407	.8168	.0480	.1041
3.	89851.	2673.	.2928	.0448	1.1848	.0403	.1552
4.	89743.	3550.	.4470	.0568	1.5136	.0576	.2006
5.	89926.	5333.	1.1146	.0981	2.2336	.0701	.3173
6.	89599.	7186.	2.5988	.1400	2.5614	.1112	.4639
7.	129937.	1071.	-.1088	.1326	.6948	.0559	.0909
8.	130381.	1791.	-.0573	.1273	1.1142	.0588	.1427
9.	129253.	2673.	.3209	.0939	1.7020	.0741	.2204
10.	130697.	3571.	.7306	.0678	2.1936	.0948	.2938
11.	129751.	5333.	1.5260	.1185	3.4033	.1073	.4740
12.	129524.	7186.	2.8747	.1730	4.2220	.1574	.6491
13.	160453.	1075.	-.3616	.1863	.7194	.1007	.1052
14.	160511.	1775.	-.3052	.0636	1.3966	.1028	.1817
15.	159848.	2703.	.2015	.0930	2.0047	.1104	.2561
16.	160202.	3593.	.8448	.0903	2.7989	.0743	.3714
17.	160190.	5333.	1.7033	.1544	4.0309	.1093	.5560
18.	159617.	7229.	3.2465	.1990	5.3656	.2071	.7969
19.	209748.	1068.	-.7225	.1387	.6905	.3073	.1321
20.	210384.	1791.	-.4774	.1364	1.7642	.1474	.2328
21.	209743.	2691.	.0695	.1956	2.4081	.2199	.3067
22.	210152.	3604.	.8771	.1201	3.4811	.1679	.4562

23.	209659.	5310.	1.9344	.2201	5.1243	.2565	.6962
24.	210445.	7186.	4.1539	.3010	7.0545	.3265	1.0408
25.	263412.	1068.	-1.3852	.2035	.7521	.2804	.2037
26.	262697.	1786.	-.8476	.1329	1.9696	.1736	.2729
27.	264503.	2661.	-.3776	.0990	2.7347	.1082	.3508
28.	263296.	3571.	.8929	.2176	4.2451	.1581	.5516
29.	261772.	5310.	2.0120	.3024	5.9830	.2993	.8027
30.	260487.	7186.	4.1070	.3788	7.9955	.4096	1.1425

B.5 Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 5.

SAWTOOTH PATTERN #5
105 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.64
DR. D. CHILDS TEXAS A&M SEPT. 1985

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	¦F¦ (kN)
1.	89694.	1075.	-.2429	.0543	.4239	.1015	.0627
2.	89595.	1786.	-.1085	.0668	.5396	.0835	.0705
3.	89452.	2661.	.0378	.0277	.8228	.0363	.1047
4.	90591.	3571.	.2555	.0509	1.1804	.0662	.1535
5.	90043.	5333.	1.3510	.1082	1.5101	.0947	.2578
6.	90474.	7186.	2.5731	.1432	1.6044	.1232	.3855
7.	130249.	1068.	-.5128	.1041	.5779	.0670	.0992
8.	130350.	1786.	-.4305	.1100	.9528	.0905	.1334
9.	129535.	2691.	-.1723	.0681	1.3277	.1277	.1701
10.	130166.	3571.	.1453	.0793	1.7362	.0792	.2215
11.	130483.	5333.	1.2595	.1162	2.3494	.0765	.3390
12.	129992.	7186.	2.6907	.1973	2.7045	.1180	.4848
13.	159518.	1083.	-.6480	.6164	.5621	.6032	.1382
14.	159971.	1796.	-.5469	.0788	1.1539	.0840	.1626
15.	160017.	2709.	-.2921	.1330	1.6712	.1314	.2163
16.	160239.	3561.	-.2920	.1422	2.2013	.1349	.2826
17.	159924.	5310.	1.0018	.1054	3.1932	.0900	.4253
18.	160463.	7186.	2.7271	.1926	3.4986	.1596	.5639
19.	250029.	1060.	-1.9164	.1608	1.0751	.2632	.2815
20.	250449.	1760.	-1.7491	.1457	2.0047	.1357	.3385
21.	250586.	2661.	-1.5988	.0860	2.6131	.2015	.3891
22.	250478.	3529.	-.7748	.1445	3.3906	.1794	.4421

23.	249919.	5310.	.5785	.2005	4.8939	.1998	.6265
24.	250552.	7186.	1.9629	.2373	6.2416	.2082	.8315
25.	342151.	1083.	-3.6912	.3356	1.1616	.4206	.4952
26.	341964.	1780.	-3.4752	.2534	2.9152	.1977	.5773
27.	341768.	2679.	-3.2849	.2143	3.7743	.1441	.6363
28.	348323.	3509.	-2.3883	.2487	4.8151	.1925	.6833
29.	345254.	5286.	-.7160	.3336	7.0402	.2415	.8997
30.	346465.	7186.	1.4159	.3909	9.1342	.3375	1.1752

B.6 **Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 6.**

SAWTOOTH PATTERN #6
80 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.49
DR. D. CHILDS TEXAS A&M SEPT. 1985

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (KN)
1.	89904.	1075.	-.2428	.0452	.3922	.0310	.0590
2.	89559.	1780.	-.1640	.0201	.8101	.0291	.1050
3.	89949.	2667.	.1258	.0266	1.0599	.0214	.1356
4.	90408.	3561.	.2513	.0243	1.1049	.0291	.1439
5.	90398.	5310.	1.3542	.0928	1.5974	.0732	.2663
6.	90536.	7186.	2.6642	.1474	1.8295	.1115	.4107
7.	129814.	1060.	-.6009	.0554	.6237	.0564	.1104
8.	129670.	1802.	-.4959	.0322	1.1285	.0393	.1566
9.	130198.	2740.	-.1752	.0535	1.5935	.0624	.2037
10.	130323.	3659.	.1097	.0298	1.8638	.0286	.2371
11.	130529.	5310.	1.2352	.2000	2.5946	.1085	.3661
12.	129843.	7186.	2.8381	.1246	2.9495	.1312	.5201
13.	160478.	1095.	-.8296	.0870	.8094	.0901	.1480
14.	159645.	1796.	-.6893	.0360	1.4355	.0526	.2023
15.	159797.	2685.	-.4222	.0582	1.7799	.0715	.2325
16.	159824.	3571.	-.1495	.0800	2.4869	.0607	.3166
17.	159728.	5286.	1.0656	.1075	3.3844	.0949	.4509
18.	159795.	7186.	2.8270	.1435	3.9111	.1550	.6132
19.	250011.	1064.	-2.0770	.1488	1.1664	.2411	.3045
20.	249754.	1813.	-2.1234	.0698	2.4083	.0723	.4079
21.	250207.	2685.	-1.7311	.0991	3.1476	.1238	.4564
22.	249704.	3582.	-1.2256	.1176	3.9961	.0975	.5310

23.	250461.	5286.	.4805	.2202	5.6431	.1813	.7199
24.	250472.	7186.	2.6422	.2691	7.2731	.2907	.9833
25.	319217.	1075.	-3.3762	.2210	1.2037	.5337	.4610
26.	318603.	1765.	-3.3778	.0865	3.0166	.1084	.5752
27.	318386.	2661.	-2.8058	.1318	3.7299	.1588	.5930
28.	318097.	3561.	-1.9027	.0823	5.2254	.1094	.7064
29.	317945.	5286.	-.3880	.2977	7.1193	.2252	.9063
30.	326332.	7186.	1.5906	.3084	9.0815	.2816	1.1714

B.7 **Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 7.**

SAWTOOTH PATTERN #7
55 TEETH, TOOTH DEPTH= 1.016mm, GAMMA=0.34
DR. D. CHILDS TEXAS A&M SEPT 1985

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (KN)
1.	90146.	1049.	-.1885	.0331	.4038	.0212	.0568
2.	89900.	1760.	-.0180	.0119	.5279	.0131	.0671
3.	89730.	2655.	.0386	.0220	.8061	.0151	.1025
4.	90333.	3614.	.2395	.0285	1.0822	.0412	.1408
5.	89795.	5310.	1.1939	.0518	1.3393	.0521	.2280
6.	89490.	7186.	2.5892	.0950	1.4332	.0942	.3761
7.	129942.	1103.	-.5291	.0818	.7082	.0636	.1129
8.	129885.	1818.	-.2062	.0278	1.0784	.0426	.1395
9.	129600.	2703.	-.1603	.0426	1.3887	.0507	.1776
10.	129474.	3647.	.1378	.0436	1.8324	.0473	.2334
11.	130412.	5310.	1.0933	.0746	2.2487	.0886	.3176
12.	130163.	7186.	2.7070	.1394	2.6979	.1284	.4857
13.	160491.	1079.	-.6738	.1100	.8992	.0845	.1438
14.	159935.	1807.	-.5266	.0336	1.2131	.0356	.1680
15.	160023.	2697.	-.2680	.0457	1.6512	.0439	.2125
16.	159689.	3604.	-.0182	.0493	2.3575	.0908	.2995
17.	159637.	5333.	1.0791	.1307	2.9079	.1099	.3942
18.	159802.	7186.	2.6591	.1383	3.5114	.1135	.5596
19.	249864.	1068.	-1.6280	.2281	1.3813	.2740	.2748
20.	249995.	1786.	-1.3198	.0658	2.1552	.0708	.3211
21.	249438.	2697.	-1.1767	.0881	2.8528	.0736	.3921
22.	249675.	3604.	-.8644	.1157	3.8050	.1453	.4957

23.	250091.	5310.	.6994	.1446	5.0816	.1413	.6517
24.	250387.	7186.	2.8670	.2491	6.6076	.2204	.9155
25.	360377.	1060.	-3.2681	.3720	2.3414	.5033	.5164
26.	359987.	1796.	-2.6127	.1456	3.5660	.1585	.5618
27.	368740.	2614.	-2.4214	.1505	4.5741	.2273	.6576
28.	360949.	3550.	-2.2686	.1354	5.4884	.1414	.7545
29.	361197.	5333.	-.3481	.4651	7.6058	.1924	.9689
30.	360998.	7186.	2.2756	.4110	10.3391	.3861	1.3456

B.8 **Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 8.**

SAWTOOTH PATTERN #8
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.48
DR. D. CHILDS TAMU NOV 1985

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (kN)
1.	90421.	1099.	-.2770	.0822	.5198	.0477	.0758
2.	90240.	1835.	-.1495	.0251	.9470	.0247	.1218
3.	89601.	2685.	.0206	.0265	1.2509	.0216	.1589
4.	90342.	3670.	.2531	.0600	1.6433	.0318	.2113
5.	89617.	5310.	.8006	.0576	2.2892	.0518	.3080
6.	90300.	7186.	2.6070	.1250	2.0369	.1218	.4204
7.	129835.	1064.	-.4438	.0949	.6878	.0649	.1050
8.	129913.	1840.	-.4145	.0413	1.2921	.0847	.1724
9.	130188.	2697.	-.0148	.0391	1.8158	.0343	.2307
10.	130034.	3571.	.2459	.0524	2.3934	.0711	.3056
11.	129444.	5310.	.9025	.0776	3.3057	.1061	.4353
12.	130024.	7229.	2.1307	.5309	4.1654	.2971	.5987
13.	159844.	1071.	-.6408	.1023	.8040	.0855	.1316
14.	160109.	1802.	-.6945	.0322	1.4635	.0309	.2058
15.	160300.	2685.	-.2018	.0502	2.2265	.0439	.2840
16.	159739.	3659.	.1987	.0852	3.2030	.0699	.4076
17.	159515.	5310.	1.0132	.1077	4.3521	.0960	.5677
18.	159826.	7186.	2.6380	.2436	5.1616	.2330	.7368
19.	219832.	1075.	-1.3020	.1946	.9744	.2594	.2105
20.	219848.	1796.	-1.0907	.0683	2.0583	.0834	.2959
21.	220500.	2697.	-.8263	.0800	2.9492	.0857	.3891
22.	219671.	3540.	-.3139	.0668	3.9239	.1324	.5000

23.	220501.	5310.	1.1671	.2184	5.7964	.2415	.7515
24.	219590.	7186.	2.9801	.3276	7.5675	.2975	1.0337
25.	275099.	1079.	-2.0089	.1760	.9477	.3658	.2867
26.	274109.	1807.	-1.6003	.0841	2.5623	.0681	.3839
27.	278546.	2691.	-1.7119	.1002	3.7772	.0869	.5268
28.	282887.	3582.	-1.0689	.1920	5.2721	.1331	.6836
29.	287765.	5310.	.5992	.3132	7.5331	.2457	.9605
30.	294829.	7186.	3.0728	.3946	10.4945	.3536	1.3898

B.9 Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 9.

SAWTOOTH PATTERN #9
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=.68
DR. D. CHILDS TAMU NOV 1985

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (KN)
1.	90025.	1075.	-.1662	.0651	.4765	.0270	.0647
2.	90385.	1813.	-.0049	.0249	.9696	.0344	.1232
3.	89822.	2697.	.3533	.0320	1.2783	.0315	.1685
4.	90204.	3636.	.5116	.0510	1.7293	.0674	.2291
5.	90524.	5286.	1.3502	.0965	2.0559	.0857	.3126
6.	89579.	7186.	3.0941	.1007	2.5493	.0989	.5093
7.	130238.	1064.	-.4046	.1062	.6811	.0672	.1018
8.	129722.	1813.	-.3150	.0345	1.3334	.0501	.1741
9.	129504.	2691.	.1757	.0417	1.7888	.0421	.2283
10.	130339.	3604.	.5751	.0587	2.4917	.0581	.3248
11.	130226.	5286.	1.6127	.1479	3.6083	.1138	.5024
12.	130349.	7186.	3.1037	.1153	4.2306	.1549	.6667
13.	160522.	1087.	-.6372	.1430	.7543	.1171	.1275
14.	160448.	1796.	-.4252	.0542	1.4571	.0632	.1929
15.	160071.	2721.	-.1676	.0858	2.2722	.0739	.2896
16.	160217.	3604.	.5086	.0922	2.8835	.0887	.3720
17.	159832.	5310.	1.7967	.2548	4.3549	.1601	.5991
18.	160556.	7186.	3.4113	.1852	5.7700	.1507	.8516
19.	219844.	1068.	-1.1798	.1124	.7985	.1704	.1827
20.	220184.	1796.	-1.0163	.0818	2.1634	.0940	.3037
21.	219780.	2679.	-.5540	.0922	2.8926	.1289	.3742
22.	219943.	3571.	-.1038	.0981	3.8062	.1331	.4837

23.	219499.	5310.	1.8319	.2489	5.7792	.1587	.7707
24.	219909.	7186.	4.4753	.2951	8.2919	.3144	1.1972
25.	247822.	1099.	-1.5328	.1674	.7071	.3233	.2191
26.	248663.	1796.	-1.3262	.0736	2.5290	.0664	.3628
27.	249055.	2709.	-1.0485	.0903	3.2961	.1311	.4394
28.	250979.	3604.	-.2447	.1139	4.4977	.1671	.5722
29.	256905.	5310.	1.4111	.3232	6.6456	.1830	.8638
30.	260000.	7186.	4.1050	.3307	9.5686	.3259	1.3229

C-2

B.10 Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 10.

SAWTOOTH PATTERN #10
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.33
DR. D. CHILDS TAMU DEC 1985

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	!F! (KN)
1.	90448.	1079.	-.2791	.0630	.4582	.0420	.0688
2.	90287.	1807.	-.0825	.0194	.6835	.0252	.0875
3.	89865.	2721.	.0542	.0330	1.1516	.0249	.1465
4.	90011.	3571.	.3346	.0272	1.1974	.0243	.1579
5.	89708.	5333.	1.4122	.0720	1.7962	.0649	.2903
6.	89970.	7186.	3.0426	.0846	2.5029	.0725	.5004
7.	129994.	1087.	-.6483	.0874	.6443	.0879	.1171
8.	129751.	1796.	-.4741	.0267	1.0775	.0279	.1495
9.	129678.	2691.	-.0844	.0342	1.6338	.0630	.2078
10.	129671.	3636.	.0969	.0334	1.9790	.0304	.2517
11.	129844.	5333.	1.1867	.1297	2.9258	.1089	.4012
12.	129959.	7186.	3.0463	.1319	3.9278	.1366	.6316
13.	160282.	1095.	-.9556	.1365	.7032	.1782	.1532
14.	159893.	1802.	-.8728	.0343	1.3094	.0314	.1999
15.	159895.	2752.	-.4855	.0417	2.0466	.0787	.2672
16.	160100.	3593.	-.0225	.0462	2.5504	.0426	.3240
17.	159957.	5310.	.9793	.0943	3.6290	.1218	.4776
18.	160393.	7186.	2.6540	.1726	5.2192	.1837	.7438
19.	219714.	1071.	-1.8094	.1471	.9763	.2811	.2641
20.	219872.	1813.	-1.7343	.0571	2.1338	.0614	.3493
21.	219994.	2727.	-1.3052	.0602	2.6727	.0700	.3778
22.	219907.	3614.	-.6576	.0773	3.4937	.1142	.4515

23.	219754.	5310.	.9285	.1199	5.1615	.1052	.6661
24.	219676.	7186.	2.4451	.2008	7.0410	.2156	.9469
25.	311309.	1095.	-3.6021	.2571	.9627	.7483	.4837
26.	313196.	1775.	-3.2822	.0964	2.5697	.0958	.5296
27.	313344.	2709.	-3.5872	.1887	3.5327	.1640	.6397
28.	315782.	3593.	-2.1249	.1221	5.2804	.1902	.7231
29.	320554.	5310.	-.6450	.1722	7.5629	.1729	.9642
30.	326006.	7186.	2.1677	.5610	10.6522	.4559	1.3826

B.11 Test Data: Force Coefficients (average and standard deviations) and average force magnitudes for stator 11.

SAWTOOTH PATTERN #11
60 TEETH, TOOTH DEPTH= 1.524mm, GAMMA=0.47
DR. D. CHILDS TAMU JAN 1986

Case	Rao	CPM (Cyc/min)	Fr/A (MN/M)	dev. (MN/M)	Fo/A (MN/M)	dev. (MN/M)	|F| (KN)
1.	90088.	1060.	-.3057	.0616	.3893	.0552	.0637
2.	89892.	1796.	-.2322	.0323	.9963	.0439	.1300
3.	89638.	2685.	-.0261	.0401	1.3490	.0533	.1714
4.	90252.	3604.	.1876	.0516	1.6780	.0701	.2145
5.	90153.	5357.	1.7287	.1312	1.9871	.1160	.3350
6.	89817.	7186.	3.4147	.0997	2.7566	.1008	.5575
7.	129545.	1091.	-.6800	.0903	.6436	.0924	.1200
8.	130490.	1791.	-.6329	.0352	1.2873	.0301	.1822
9.	130356.	2721.	-.3023	.0426	1.7264	.0692	.2227
10.	129803.	3593.	-.2012	.0565	2.4495	.0446	.3122
11.	129941.	5333.	.9991	.0947	3.6536	.0876	.4812
12.	129888.	7229.	2.9023	.5426	4.2152	.3813	.6549
13.	159641.	1083.	-1.0642	.0999	.7268	.1419	.1651
14.	160328.	1807.	-1.1218	.0473	1.5500	.0488	.2431
15.	159981.	2721.	-.7751	.0569	2.0200	.0764	.2749
16.	159853.	3604.	-.3050	.0688	2.7808	.0995	.3554
17.	160505.	5333.	.8702	.1552	4.4805	.1045	.5800
18.	159530.	7186.	2.5992	.1678	6.0616	.2064	.8378
19.	219676.	1071.	-1.7671	.1549	.8458	.3135	.2527
20.	220351.	1770.	-1.9913	.0929	1.9625	.0955	.3552
21.	220126.	2709.	-1.8773	.0942	2.9265	.1121	.4417
22.	220514.	3561.	-1.2498	.1056	3.5629	.0759	.4798

23.	219699.	5333.	.3923	.2103	5.4947	.1937	.7002
24.	220430.	7229.	2.1311	1.0810	8.4606	.3773	1.1169
25.	268397.	1075.	-2.9964	.1241	.7916	.4496	.3979
26.	266227.	1796.	-2.7212	.1119	2.6429	.1211	.4820
27.	269980.	2685.	-2.9058	.1385	3.5923	.1187	.5871
28.	271234.	3582.	-1.9866	.0912	4.4325	.1619	.6170
29.	273933.	5333.	-.4700	.2866	6.6910	.1556	.8526
30.	283076.	7186.	2.2977	.3438	10.4621	.3529	1.3609

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