

Important Scaling Parameters for Testing Model-Scale Helicopter Rotors

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An investigation into the effects of aerodynamic and aeroelastic scaling parameters on model-scale helicopter rotors has been conducted in the NASA Langley Research Center Transonic Dynamics Tunnel. The effect of varying Reynolds number, blade Lock number, and structural elasticity on rotor performance has been studied, and the performance results are discussed herein for two different rotor blade sets at two rotor advance ratios. One set of rotor blades was rigid and the other set of blades was dynamically scaled to be representative of a main rotor design for a utility class helicopter. The investigation was conducted by wind-tunnel simulations of forward flight at rotor advance ratios of 0.15 and 0.35. Additionally, the rotors were tested over a range of nominal test medium densities from 0.00382 to 0.009 slugs/ft³. This range of densities permits the acquisition of data for several Reynolds and Lock number combinations.

Nomenclature

A	= balance axial force, lb
a	= speed of sound, ft/s
a_0	= airfoil section lift curve slope
C_D	= rotor drag coefficient, $D/\rho\pi R^2(\Omega R)^2$
C_L	= rotor lift coefficient, $L/\rho\pi R^2(\Omega R)^2$
C_Q	= rotor torque coefficient, $Q_R/\rho\pi R^3(\Omega R)^2$
c	= nominal blade chord, ft
D	= rotor drag, $N \sin \alpha_s + A \cos \alpha_s$, lb
d	= rotor diameter, ft
e	= flapping hinge offset, percent radius
I_b	= blade mass moment of inertia about the flapping hinge, slug · ft ²
$\int_e^R mr^2 dr$	
L	= rotor lift, $N \cos \alpha_s - A \sin \alpha_s$, lb
M_{tip}	= rotor tip Mach number in hover, $\Omega R/a$
$M_{1,90}$	= rotor tip Mach number at $\psi = 90$ deg
N	= balance normal force, lb
Q_R	= rotor shaft torque, ft · lb
R	= rotor radius, ft
Re	= Reynolds number, $\rho V / \mu_0$, per foot
$Re_{1,90}$	= rotor tip Reynolds number at $\psi = 90$ deg, per foot
r	= spanwise distance along blade radius from center of rotation, ft
V	= freestream velocity, ft/s
z	= distance from wind-tunnel floor to rotor plane of rotation, ft
α_s	= rotor shaft angle of attack, positive tilted aft, deg
γ	= rotor blade Lock number, $\rho a_0 c R^4 / I_b$
θ	= rotor blade collective pitch angle at $r/R = 0.75$, deg
θ_t	= twist angle built into rotor blade, positive nose up, deg
μ	= rotor advance ratio, $V/\Omega R$
μ_0	= viscosity, lb · s/ft ²
ρ	= test-medium mass density, slug/ft ³
ψ	= rotor blade azimuth angle, deg
Ω	= rotor rotational velocity, rad/s

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Introduction

In general, the development of any new aircraft and, in particular, a new helicopter rotor system, requires large amounts of analysis and testing. As rotor technology has developed, new rotor systems have become increasingly complex. Today's newer rotor systems often include hingeless or bearingless hubs, the rotor blades incorporate unique planform and twist geometries, and the systems utilize advanced airfoils. Therefore, it is desirable to test model-scale rotors to verify a candidate design before committing large amounts of resources to full-scale design verification testing. The use of model-scale rotors to achieve this design verification is cost effective and also permits a much easier variation of model parameters to conduct design studies and optimizations. However, to obtain the maximum benefit from the model-scale testing of helicopter rotor systems, great attention must be paid to the aerodynamic environment in which the model is tested. When testing a model-scale rotor system, some compromises will have to be made. It is up to the model designer and test engineer to determine which parameters are most important. In considering the calculation of rotor performance coefficients for a model-scale rotor, the most important parameters are those involved with matching the correct aerodynamic forces, namely Mach number and Reynolds number. In addition, rotor blade Lock number and elasticity ensure that the rotor has the correct aerodynamic damping and aerodynamic coupling characteristics.¹ Thus, for the measurement of rotor loads, Lock number and rotor blade elasticity should also be considered.

For performance testing at model scale, matching the full-scale tip Mach number is required to duplicate compressibility effects and also to minimize the reduction in Reynolds number. The importance of simulating the correct tip Mach number is especially dependent on the rotor airfoils selected due to the relatively high Mach numbers encountered by the advancing blade. The reduced scale of the model leads to much higher model rotor speed to achieve the desired tip Mach number. This means that the rotational velocity of the scale model must be multiplied by the reciprocal of the geometric scale factor. For example, the rotational velocity of a one-fifth-size model-scale rotor would be five times that of the full-scale helicopter. This in turn leads to high centrifugal loads on the model. Additionally, it is not possible to match both full-scale tip Mach numbers and Reynolds numbers with a model-scale rotor being tested in air at atmospheric pressures and density.

The importance of Reynolds number in considering flow similarity has been well established in fixed-wing aerodynamics. However, its effect on rotary-wing aerodynamics is not as well understood. As of 1972, few comparisons had been made between full-scale data and model-scale data.² As recently as 1985, Carr³ stated that little had been done to determine the influence of Reynolds number

on dynamic stall because it is difficult to vary Reynolds number significantly without affecting compressibility effects as well. Unsteadiness can also have a significant effect on transition. Therefore, proper representation of the Reynolds number effect on dynamic stall remains an important, and presently unsolved, question. This further raises a question about the accuracy of rotor performance estimates at the extreme edges of a rotor's operating envelope.

A few effects of Reynolds number on model-scale rotor testing are known. Keys et al.⁴ state that in air, even though model rotors are tested at full-scale tip Mach numbers, the Reynolds number is low by the ratio of the geometric scale factor. This is the primary cause of differences between full-scale rotor performance and model-scale rotor test data. The difference between model-scale and full-scale performance data consists of an incremental profile power variation at zero thrust and an additional induced power increment that is a function of the lift coefficient. Another example of the variation in power with lift coefficient and Reynolds number occurs in models with tapered tips. The very low Reynolds number of the tapered tip can cause premature separation that does not occur at full scale. In forward flight, unsteady aerodynamic stall delay effects are much larger at model scale than at full scale. Thus, it has been shown that even though model-scale rotors can be tested at full-scale tip Mach numbers, the lower Reynolds number at model scale can have a powerful effect on the measurement of rotor performance coefficients.

According to Bingham and Kelley,⁵ the effects of Reynolds number on the performance of scaled model rotors increases with increasing forward flight velocity and decreases with increasing tip chord of nonrectangular blades. The Reynolds number influences become most significant as the retreating blade airfoil sections approach the maximum lift coefficients characteristic of model scale. Induced power benefits should not be significantly altered by Reynolds number variations, but the influence on profile power is substantial. However, Reynolds number influences at higher advance ratios or thrust coefficients for Bingham and Kelley's investigation did not permit direct experimental verification of the aforementioned conclusion. This lack of verification resulted in concern that model-scale test results may not be properly applied in projecting full-scale characteristics.

One method of achieving full-scale tip Mach numbers while also obtaining a relatively high Reynolds number for a scale model is

by using a heavy gas test medium.⁶ Yeager and Mantay showed that Mach number effects on model rotor data obtained in a refrigerant-12 (R-12) test medium are essentially the same as full-scale rotor aerodynamic performance data obtained in air.⁷ Yeager and Mantay also indicated that the Reynolds number effects might be minor in rotor aerodynamic performance testing compared to the combined effects of rotor solidity and blade elastic properties. Therefore, blade elastic modeling should also be considered a significant parameter in model-scale rotor aerodynamic performance testing. Finally, to fully model the complex aerodynamic environment of a helicopter rotor system, some attention must be paid to the rotor blade Lock number, which is defined as the ratio of the blade aerodynamic forces to the blade inertia forces. Correct scaling of rotor Lock number is important for the prediction of rotor loads and stability. However, its contribution to the rotor aerodynamic environment cannot be neglected because it directly affects blade flapping angles. Still, it would be desirable to isolate the various effects of Reynolds number, Lock number, and blade elasticity so as to more fully understand their total effect on predicting full-scale helicopter rotor performance and dynamic loads from scale-model rotor tests.

Even at the moderately high Mach numbers in which a typical helicopter rotor operates, the effect of Reynolds number can be significant. These effects on maximum lift coefficient are illustrated in Fig. 1 for a NACA 63-series airfoil section.⁸ The Reynolds number effect is also apparent in plots of minimum section drag coefficients. The range of Reynolds numbers achieved by testing in a heavy gas is indicated in Fig. 1, as is the typical range for model-scale rotor blades tested in air at atmospheric pressure.

A study has been conducted in the NASA Langley Research Center Transonic Dynamics Tunnel (TDT) that investigated the isolated and combined effects of varying several aerodynamic and dynamic scaling parameters.⁹ These parameters were Reynolds number, rotor blade Lock number, and blade elasticity. Two sets of geometrically similar rotor blades were tested: a rigid blade set and a set of blades that were dynamically scaled to be representative of the main rotor of a utility-class helicopter, for example, the U.S. Army UH-60 Blackhawk helicopter. This paper presents some forward flight results of that study pertinent to how the variation in Reynolds number, Lock number, and blade structural elasticity affects the performance measurements for a model-scale helicopter rotor system.

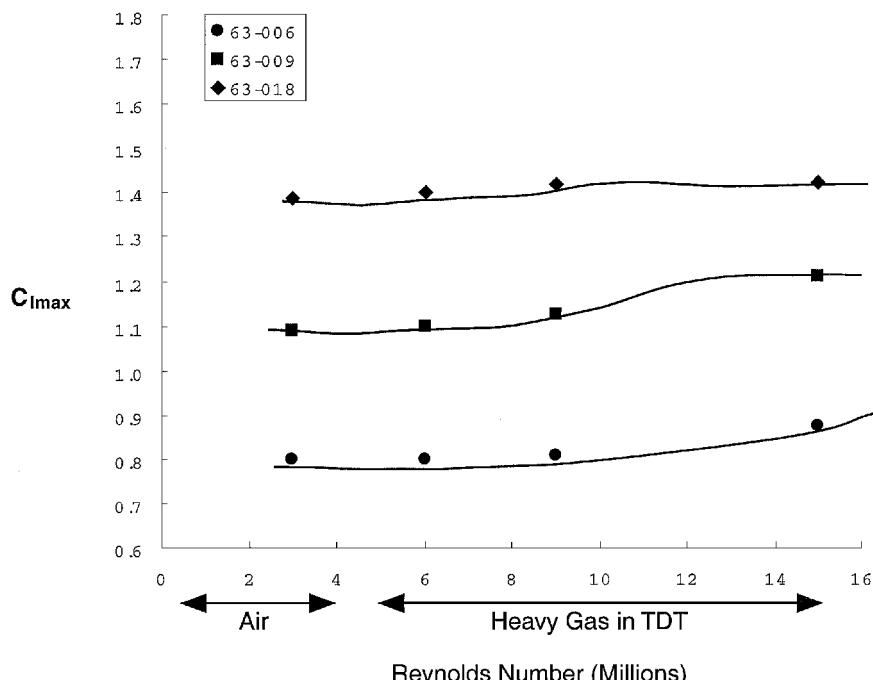


Fig. 1 Maximum lift coefficient vs Reynolds number per foot.

Test Apparatus and Procedures

The data presented herein were obtained via the Aeroelastic Rotor Experimental System (ARES) and the NASA Langley Research Center TDT. The ARES is a fly-by-wire belt-driven rotor system testbed that is used to experimentally test dynamically scaled models of up to approximately 9 ft in diameter. The TDT incorporates the use of a heavy gas test medium to permit the testing of scale-model aircraft at relatively high densities (thus higher Reynolds number), lower speed of sound, and subtle changes in the ratio of specific heats as well as viscosity. These differences ease the manufacturing requirements for building a set of model-scale rotor blades.

The TDT is a continuous-flow tunnel with a slotted test section capable of operation up to Mach 1.2 at stagnation pressures of 0.1–1.0 atm. The tunnel test section is 16 ft² with cropped corners and has a cross-sectional area of 248 ft². Currently, either air or refrigerant-134a (R-134a) may be used as the test medium. At the time that these data were taken, the TDT used R-12 as the test medium. For this study, data were taken over a range of tunnel operating densities from 0.00382 to 0.009 slugs/ft³. Because of its high density at normal atmospheric pressure and low speed of sound, the use of R-12, while matching model-scale rotor Mach number to full-scale values, provides Reynolds numbers greater than that obtainable using air. Furthermore, some restrictions on model structural design parameters are eased while maintaining dynamic similarity. The heaviest test medium permits a heavier structural density to obtain the required stiffness characteristics, and thus eases design and fabrication requirements of the model.¹⁰

The ARES has a streamlined fuselage enclosing the rotor controls and drive system. The ARES is powered by a variable-frequency synchronous motor rated at 47 hp output at 12,000 rpm. The motor is connected to the rotor shaft through a belt-driven two-stage speed reduction system. The ARES rotor control system and rotor shaft angle of attack are remotely controlled from the wind-tunnel control room. The model rotor shaft angle of attack is varied by an electrically controlled hydraulic actuator. Blade collective pitch and lateral and longitudinal cyclic pitch are input to the rotor through a swashplate. The swashplate is moved by three hydraulic actuators.

Instrumentation on the ARES allows continuous displays of model rotor control settings, rotor moments and forces, blade structural moments, and pitch link loads. The ARES rotor shaft pitch

attitude is measured by a static accelerometer, and rotor control positions are measured by linear potentiometers connected to the swashplate. Rotor blade flapping and lagging are measured by rotary potentiometers mounted on the rotor hub and geared to the rotor yoke. Rotor shaft speed is determined by a magnetic sensor. The rotating blade data are transferred through a 30-channel slip-ring assembly. Rotor forces and moments are measured by a six-component strain-gauge balance mounted below the rotor pylon and drive system. The balance is fixed with respect to the rotor shaft and pitches with the fuselage, and, by design, fuselage forces and moments are not sensed.

The model rotor hub used in this investigation is a four-bladed articulated hub with coincident lead-lag and flapping hinges. The hub was operated with a pitch-flap coupling ratio of 0.5 (flap up, pitch down). The attachment point of the blade pitch link was 1.4 in. aft of the blade pitch axis.

Two blade sets were used for this evaluation and both blade sets were one-sixth-size and Mach-scaled representations of UH-60A rotor blades. The first blade set was a dynamically scaled (elastic) version of the UH-60A rotor. The second blade set was designed to be approximately four times more stiff in flapwise bending and approximately twice as stiff in chordwise bending and torsion as the elastic blade set. These blades are referred to as the rigid blade set. The dynamic characteristics of the rigid blade set do not represent actual helicopter blades in terms of flapwise (out-of-plane), chordwise (in-plane), or torsional stiffness. They were included in the investigation solely to isolate the effects of structural elasticity. Both blade sets were untapered with a 20-deg swept tip outboard of the 94%-radius station and used SC1095 and SC1094R8 airfoils (Fig. 2). Aerodynamic characteristics of these airfoils are documented by Noonan and Bingham.¹¹ The area, thrust-weighted, and torque-weighted solidities for the rotor were each 0.0825. Planform geometry and twist distribution of these blades are shown in Fig. 2. One blade of each blade set was instrumented with resistance-wire strain-gauge bridges calibrated to measure blade structural moments. These gauges were used to monitor limit loads for safety considerations. Embedded in each rigid blade were four hollow steel tubes, two extending along the leading edge and two along the trailing edge of the blade spar centered about the quarter-chord. These tubes allowed for distributed nonstructural mass to be added to the blades from the blade root to 80% radius. Steel or tungsten rods were

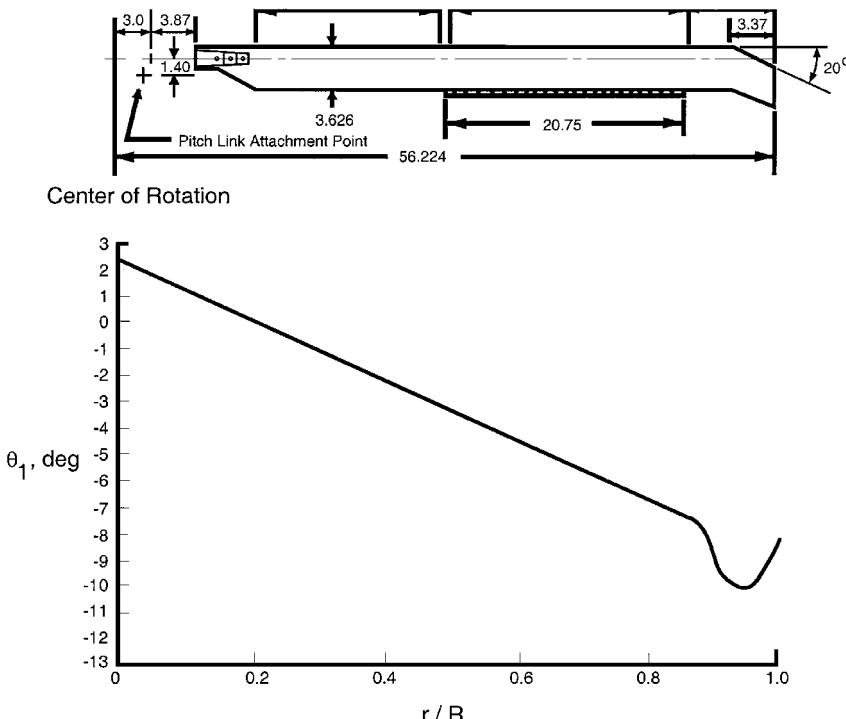


Fig. 2 Model helicopter rotor blades.

inserted into these tubes to ballast the blade to obtain the desired Lock number for the tunnel test medium operating density.

Testing Methods and Data Reduction

The focus of this investigation was to examine the effects of Mach number, Lock number, Reynolds number, and dynamic scaling on rotor performance. Therefore, both blade sets were evaluated over the same range of nominal test conditions defined by tip Mach number, rotor lift coefficient, and rotor drag coefficient or propulsive force. Each blade set was ballasted for a specific test medium density. At each test point, the rotor rotational speed and tunnel conditions were adjusted to give the desired values of M_{tip} and rotor advance ratio. Blade collective pitch and shaft angle of attack were then swept to obtain variations in rotor lift and propulsive force. At each collective pitch and shaft angle setting, the cyclic pitch was used to remove rotor first-harmonic flapping with respect to the rotor shaft, and then data were recorded. The maximum value of collective pitch attained at each shaft angle of attack was determined in most cases by either blade load limits or the ARES drive system limits. Rotor aerodynamic performance and blade loads were measured in forward flight at advance ratios of 0.15 and 0.35 for a range of shaft angles from 0 to -11.8 deg. Variations in Reynolds number and Lock number were achieved by varying the tunnel operating density and/or blade ballast.

Model dead weight tares were determined throughout the range of shaft angles of attack with the blades on and then with them removed for each configuration of blade ballast. Aerodynamic rotor hub tares were determined with the blades removed throughout the ranges of shaft angle of attack and advance ratios investigated. Both dead weight and aerodynamic hub tares have been removed from the data presented herein. All data were acquired at z/d equal to 0.87. No correction has been applied to the data to account for tunnel wall effects; however, for the flight conditions tested these effects have been shown to be small.⁶ All strain-gauge and balance voltage readings were zeroed with the blades resting on the down stops and nonrotating prior to each test run. At each test point, tunnel parameter data were averaged and stored digitally. Performance data (i.e., fixed system forces and moments) were averaged and stored as digital counts. At the completion of each run, all strain-gauge and balance voltage readings were again recorded with the blades resting on the down stops and nonrotating. These final voltage readings were used to correct for any amplifier voltage drift.

The quality of the performance data obtained during this investigation with regards to repeatability and accuracy was addressed. During the test, 52 target data points were randomly selected to be repeated. The total number of actual repeat points was 102. The average deviation in C_L , C_D , and C_Q was determined from the differences between selected target values and the repeated values. The average deviations for constant values of μ , α_s , θ , and rotor cyclic pitch were determined to be as follows: $C_L \pm 0.00004$, $C_D \pm 0.00001$, and $C_Q \pm 0.00001$.

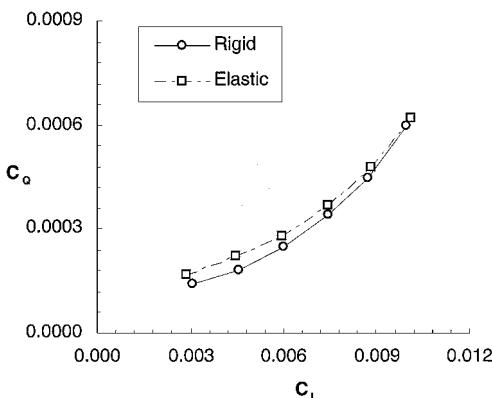


Fig. 3 Effect of rotor blade elasticity at $\theta = 0.15$ and $\alpha_s = -1.8$ deg.

Discussion of Results

Based on the results reported by Yeager and Mantay,⁷ the first parameter to be studied was the effect of rotor blade elasticity on rotor performance coefficients. As seen in Fig. 3, a small effect of varying blade stiffness is seen at low values of rotor C_L . However, at higher advance ratios this effect is not apparent (Fig. 4). As noted, the results dealing with rigid vs elastic blade sets presented herein are different than those which were originally presented by Yeager and Mantay. This may be caused by the relative differences between rigid blades in each case. The original study states that the rigid blades were an order of magnitude more stiff than the baseline blades, whereas in the case of this investigation, the rigid blades were only 2–4 times more stiff. There may also be differences because the

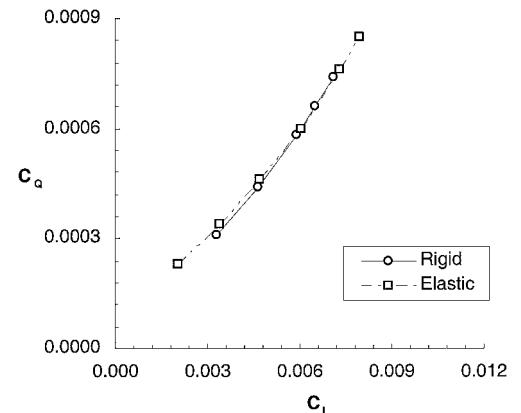


Fig. 4 Effect of rotor blade elasticity at $\theta = 0.35$ and $\alpha_s = -1.8$ deg.

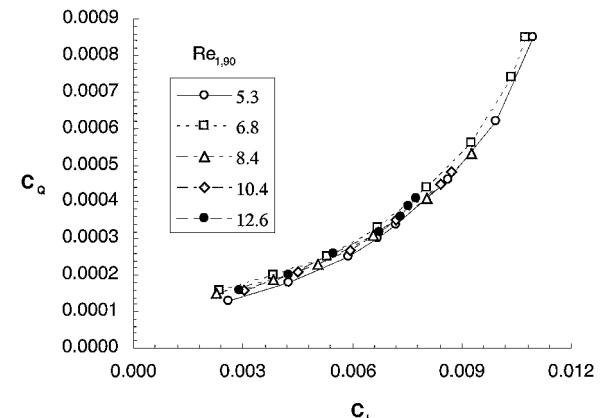


Fig. 5 Reynolds number effect on rotor torque at $\theta = 0.15$ with varying Lock number.

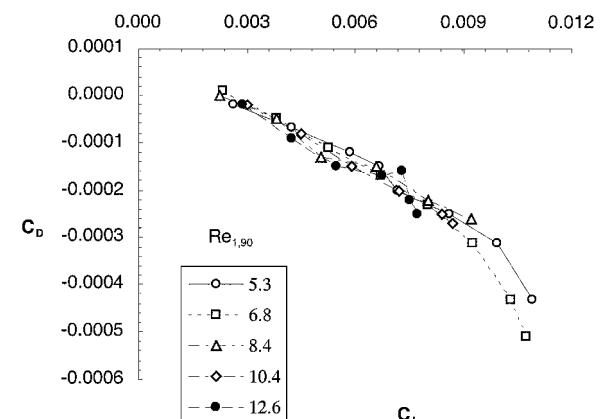


Fig. 6 Reynolds number effect on rotor drag at $\theta = 0.15$ with varying Lock number.

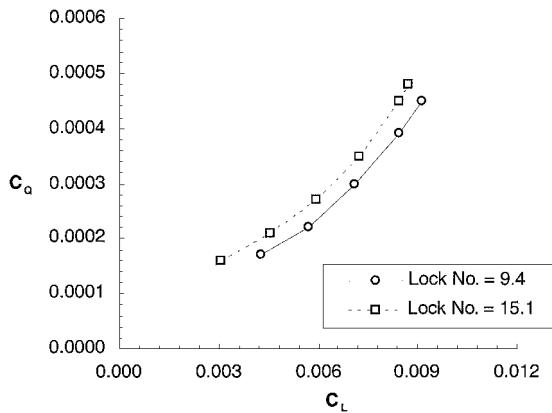


Fig. 7 Lock number effect on rotor torque at $\theta = 0.15$ at constant Reynolds number.

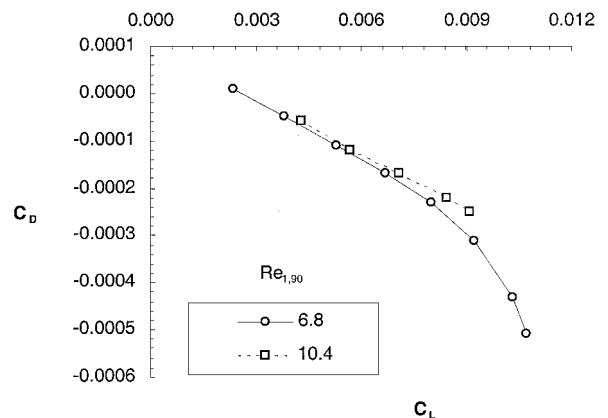


Fig. 10 Reynolds number effect on rotor drag at $\theta = 0.15$ at constant Lock number.

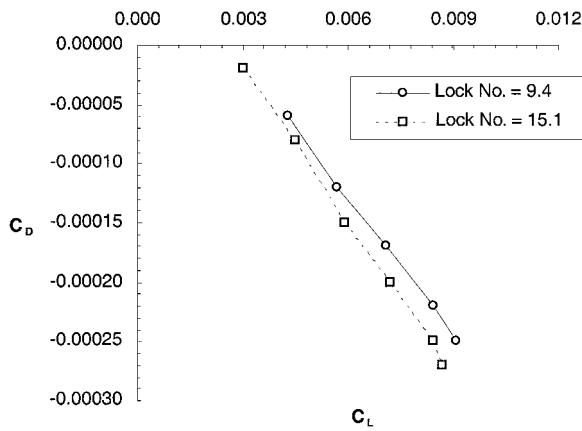


Fig. 8 Lock number effect on rotor drag at $\theta = 0.15$ at constant Reynolds number.

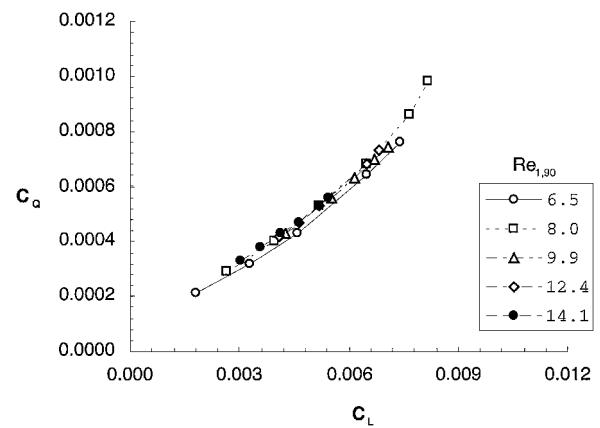


Fig. 11 Reynolds number effect on rotor torque at $\theta = 0.35$ with varying Lock number.

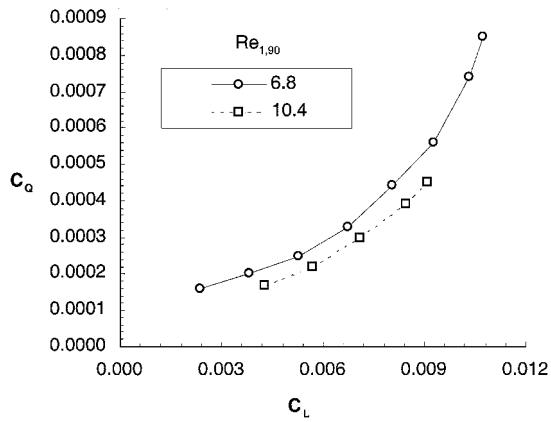


Fig. 9 Reynolds number effect on rotor torque at $\theta = 0.15$ at constant Lock number.

earlier configuration was a teetering rotor whereas this configuration is an articulated configuration.

Because of the small effects due to blade elasticity determined in this investigation it was decided to examine the effects of variations in Reynolds number and Lock number through data obtained via the rigid blade set. The data for the rigid blade set were taken over a greater range of test medium density, and, hence, a wider range of Reynolds and rotor blade Lock numbers were available for examination. Over the range of test medium densities utilized, the Reynolds number of the advancing blade tip increases from approximately 5.3 to 14.1×10^6 per foot and Lock number increases from 9.4 to 15.1 .

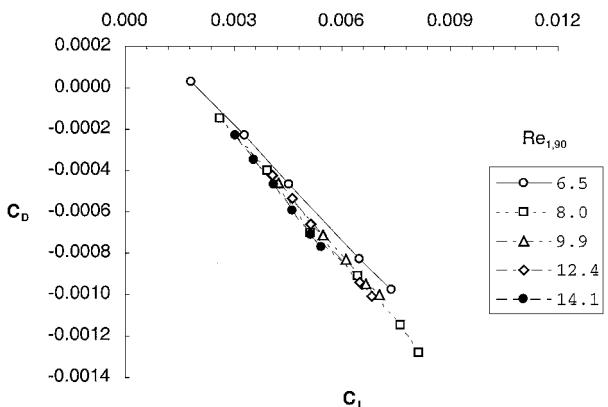


Fig. 12 Reynolds number effect on rotor drag at $\theta = 0.35$ with varying Lock number.

As test medium density is increased, the Reynolds number seen by the blade increases. If the blades are not rebalanced to give the desired Lock number then we see results such as those shown in Figs. 5 and 6 taken at $\mu = 0.15$. As can be seen in Figs. 5 and 6, there is no apparent effect of increasing Reynolds number, but Lock number is also increasing. The data presented for $\mu = 0.15$ were taken at a constant $\alpha_s = -1.8$ deg. By isolating the effects of varying Lock number while maintaining a constant Reynolds number, it can be seen that at a higher Lock number there is a definite and significant increase in rotor C_Q and C_D at a given C_L (Figs. 7 and Fig. 8). Conversely, if a constant Lock number is maintained and Reynolds number is increased, then the expected decrease in rotor C_Q at a given C_L is noted (Figs. 9 and 10). These trends were repeated at $\mu = 0.35$ as shown in Figs. 11–16. The data presented for $\mu = 0.35$ were taken at a constant $\alpha_s = -5.0$ deg.

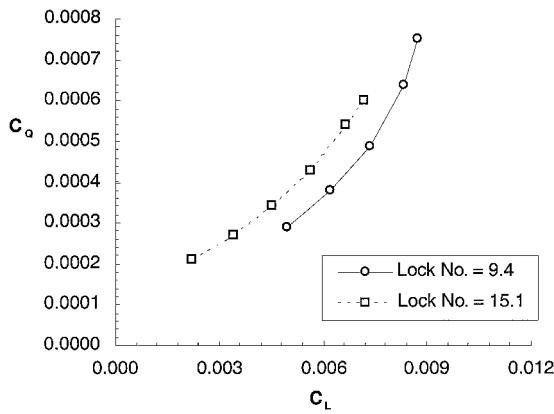


Fig. 13 Lock number effect on rotor torque at $\theta = 0.35$ at constant Reynolds number.

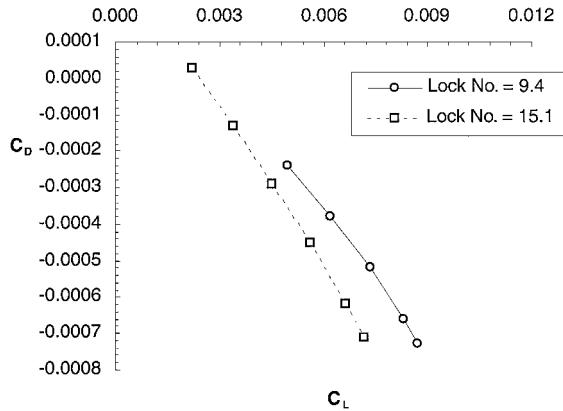


Fig. 14 Lock number effect on rotor drag at $\theta = 0.35$ at constant Reynolds number.

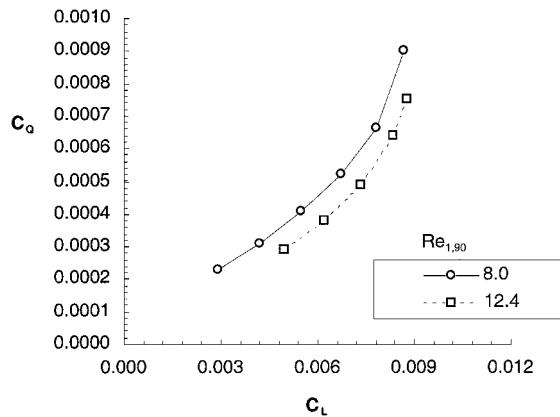


Fig. 15 Reynolds number effect on rotor torque at $\theta = 0.35$ at constant Lock number.

Based on an examination of trends using blade element theory and as presented by Gessow and Myers,¹² the trends in C_Q at constant C_L are in agreement. To be specific, the equations show that an increase in Lock number will result in an increase in C_Q and the data show the same trends. Reynolds number trends in the data also agree with theory. Rotor torque decreases with increased Reynolds number indicating a decrease in rotor blade profile drag (Figs. 9 and 15). The effect of Reynolds number is also seen in the decrease in rotor propulsive force with increased advance ratio indicating a reduction in blade drag on the retreating side of the rotor disk where viscous effects should dominate (Figs. 10 and 16).

Another way of looking at the data is to examine the effect of varying Lock and Reynolds number for a specific rotor task as

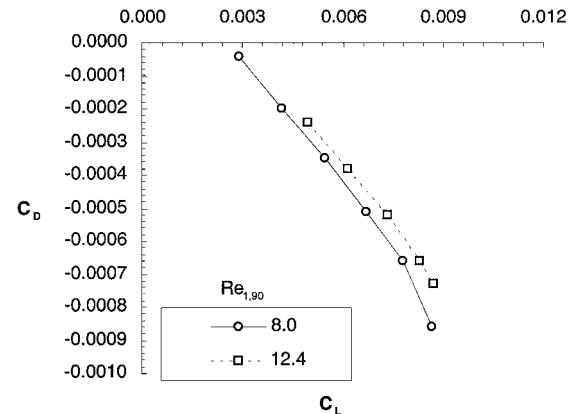


Fig. 16 Reynolds number effect on rotor drag at $\theta = 0.35$ at constant Lock number.

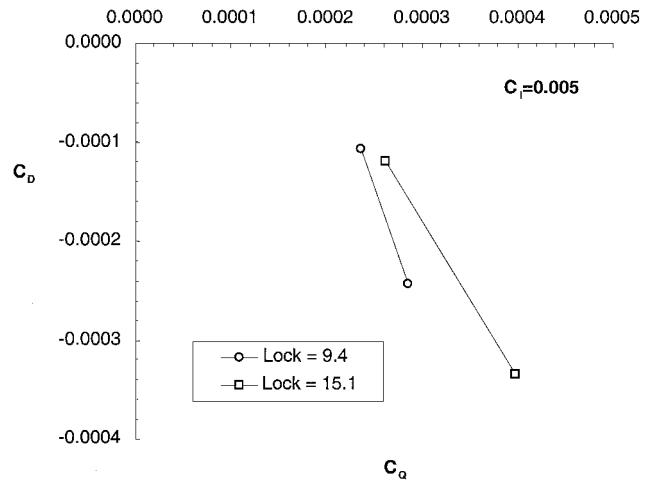


Fig. 17 Effect of Lock number at $C_L = 0.005$.

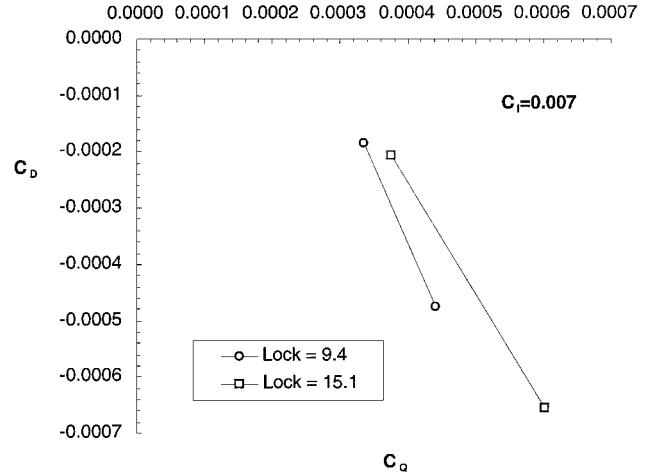


Fig. 18 Effect of Lock number at $C_L = 0.008$.

defined by constant C_L (Figs. 17–20). These data are obtained by cross plotting from rotor C_L vs C_Q and C_L vs C_D curves to generate rotor C_D vs rotor C_Q . Travel along the curves represents an increase in μ from 0.15 to 0.35 as propulsive force C_D increases (becomes more negative). Figures 17 and 18 illustrate data taken at constant tunnel operating density, and Figs. 19 and 20 show data taken at constant Lock number. Once again it is evident that both Lock and Reynolds number effects are significant at model scale. At a specified rotor task, increasing Lock number increases rotor torque required. Figures 19 and 20 are more complex

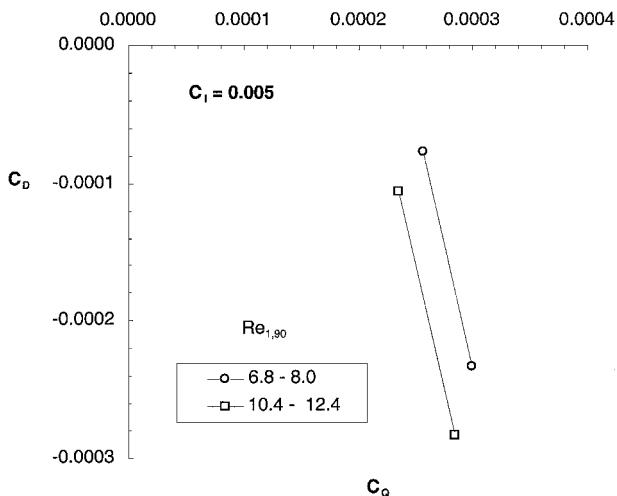


Fig. 19 Effect of Reynolds number at constant Lock number for $C_L = 0.005$.

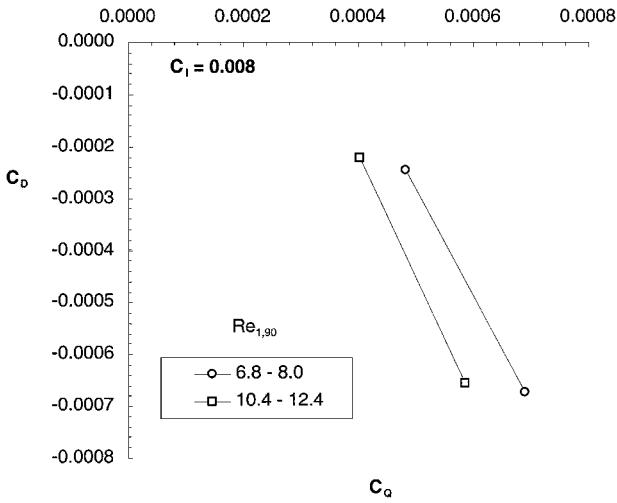


Fig. 20 Effect of Reynolds number at constant Lock number for $C_L = 0.008$.

as Reynolds number is increased due to both μ and increasing tunnel operating density. Note that at higher advance ratios the torque decrease due to increasing tunnel operating density is greater than at lower advance ratios as expected.

Conclusions

In conclusion, it has been shown that Reynolds number and Lock number effects are very important to the testing of model-scale rotor systems for helicopter rotor performance. It is well known that

it is not possible to simultaneously match all key full-scale aerodynamic parameters. The best course of action for testing model-scale rotors is to match the tip Mach number and test at as high a Reynolds number as is feasible and at the full-scale value of Lock number. Testing model-scale rotors in a heavy gas environment has also proven very successful, particularly testing rotors in R-12. The data presented herein support the following conclusions:

- 1) Reynolds number effects are important when testing model-scale rotor systems. A small decrease in rotor C_Q is indicated at a given value of rotor C_L when testing at higher Reynolds numbers.
- 2) Lock number is also an important parameter when measuring rotor performance coefficients. An increase in rotor C_Q is indicated at a given value of rotor C_L when testing at higher Lock numbers.
- 3) For the advanced blade configuration tested, it is possible to offset performance losses caused by low Reynolds number testing by adjusting Lock number for model-scale rotors. Further testing is necessary to investigate this phenomena more fully.

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