NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper n° C-4

AN EXPERIMENTAL INVESTIGATION OF MODEL ROTORS OPERATING IN VERTICAL DESCENT

by

Hong Xin and Zheng Gao
Institute of Helicopter Technology
Nanjing University of Aeronautics & Astronautics
Nanjing 210016, P.R.China

September 14-16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICAL ED ASTRONAUTICA

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SUMMARY

The helicopter behavior in the vortex-ring state has been of great concern. To get a better base for further understanding, a series of model tests were conducted on a newly-built est apparatus —— the Whirling Beam. The model rotor is a centrally-articulated one with two blades. In vertical descent, the thrust, torque, and pitch and roll moments of the model rotor were measured as the rate of descent increasing from 0 ot $1.2v_h$.Variant collective pitch angles have been settled. Either twisted (-6.5° and -9.22°) and untwisted blades were used. Further more, scaled model fuselarge of Bell-206 helicopter was made and located below the model rotor in some tests. The results obtained show that, in the vortex-ring state, the rotor thrust and torque fluctuate obviously. Existence of periodicities in the fluctuations has also been observed. The disc loading, blade twist, and the fuselage have some effects on the aerodynamic characteristics of the model rotor in the vortex-ring state.

NOTATION

V	linear velocity of model rotor, positive for descent
v	equivalent induced-velocity of the model rotor, positive down through the disc
T	rotor thrust
Q	rotor shaft torque
$\theta_{0.7}$	collective pitch angle at 70% radius
β_{1c}	longitudinal rotor disc tilt angle
β_{1s}	lateral rotor disc tilt angle
Ω	angular speed of model rotor
ω	angular speed of the beam
R	radius of the model rotor
Δ	fluctuation amplitude

Subscripts & Superscripts

$\bar{}$	mean value
$_h$	hover value

INTRODUCTION

Vertical or near-vertical descent of helicopter subjects the rotor to operation at the up-stream opposite to its induced flow. As the descent velocity is increased from hovering, the helicopter passes through the normal operation state into a less stable and unsafe region known as the vortex-ring state. The aerodynamic characteristics of a helicopter rotor operating in thevortex-ring state has been of great concern in rotorcraft engineering. Although a number of investigations have been published on this subject, there still remain many questions to be answered. The existing theories fail to give either a satisfactory explanation of the behaviour of the helicopter or an accurate prediction of the boundary of the vortex-ring state. The purpose of the experiment described herein is to measure the unsteady aerodynamic characteristics of a model rotor operating in vertical descent in order to get a better base for further understanding.

For vortex-ring experiments, the wind tunnel is not always satisfactory. First, the wall interference can not be properly modified. Second, most of the available wind tunnels usually have very poor characteristcs in low speed range required for vortex-ring state tests. A 200-meter-long track was used at University of Tokyo, on which a carriage loaded with the rotor system could move in still air. It did not have the shortcomings of the wind tunnel, but the duration of the test was limited by the length of the track.

The experiment described herein was conducted on a newly-built apparatus called the Whirling Beam (Fig.1). It has a 6-meter-long beam that rotates around a central pillar. The model rotor can be installed at variant location along the beam and move together with it in still air, modeling the turning flight of a helicopter rotor or an airplane propeller. When the model rotor is located at the far end and so has a rather large rotating radius, its motion can be considered as straight forward flight. Level, slope, or vertical flight condition can be modeled by adjusting the orientation of the axis of the model rotor (Fig.2). The effects of circular motion on the measurements is little and ignorable when rotating speed of the beam is low.The linear velocity of the model rotor can be changed by changing the rotating speed of the beam. The tests can last for any long time at a certain condition. Obviously, this is valuable for quantitative measurements. The Whirling Beam proved to be very useful and powerful formodel rotor experiments even in very low speed.

1 APPARATUS AND MODELS

1.1 The Whirling Beam

The scheme is shown in Fig.1. The hight of the central pillar is 5.5 meters, the range of the available radial location of the model rotor along the beam is from 2.4 through 6 meters, and 5-m radius was used in this experiment. The beam is driven, through a transmission box and a chain set with transmitting ratio of 125:1 totally, by a 4-kw a.c. motor controled with a frequency inverter. The rate of the beam ranges from 0 to 30 rpm.

1.2 Model Rotors and Fuselage

The model rotor selected for this experiment was a centrally articulated one with two composite blades, driven by a 550-w a.c.motor at 1400 rpm. The diameter of the rotor is 1100-mm. Three sets of blades were used in the tests. The physical characteristics of the blades are listed in the following table:

Blade	No. 1	No. 2	No. 3
Airfoil	NACA 0012	NACA 23012	OA 212
Blade Twist (deg)	0.0	-5.5	-9.22
Chord (mm)	60	73	73
Weight (g)	150	240	240

Each blade rotates around its 25% chord axis to set the pitch angle in advance. No cyclic pitch mechanism is employed. The rotor assembly is shown in Fig.3.

For examing the effects of the fuselage on the aerodynamic characteristics of the rotor in vertical descent, a scaled model fuselage of Bell-206 helicopter was made and located under its model rotor in the tests.

2 INSTRUMENTATION

The thrust, torque, and pitch and roll moments of the model rotor are measured through a strain-gage-balance system located between the motor and the hub of the rotor (Fig.3). The torque pickup, which consists of a torsion tube and four strain gages, has a maximum capacity of 0.8 kg-m. The thrust-moments pickup consists of four leaf springs and 24 strain gages. Each leaf spring has a maximum capacity of 7.5 kg. The outputs of these two pickups (for the torque outputs, through the slipper ring I shown in Fig.3 at first) are amplified by a mini-amplifier installed near the model rotor. The amplified signals are delivered to the control room through the slipper ring II shown in Fig.1, and are filtered by a low-pass filter before they are sampled by a 386/33 computer with a high-speed A/D board.

The rates of revolution of the rotor and the beam are measured with pulses. A small plate attaches on each motor shaft, it interrupts a magnetic circuit while rotating, so creating the pulse signals. These two rates of revolution are displayed on a rpm meter and sampled by the computer.

3 TESTS

The rotors were tested under the following conditions:

Blade Set	No.1	No.2	No.3
Collective Pitch (deg)	6 and 10	10	10
Fuselage	without	with and without	with and without

At each condition, the model rotor was tested in hover, vertical climb, and vertical descent. The rate of revolution of the beam was increased from 0 to 8 rpm in climb, and from 0 to 12 rpm in descent. Correspondingly, the linear speed of the model rotor was varied from -4.2 to 6.3 m/s. At each test point, the rotor was started and accelerated to 1400 rpm after the beam was adjusted to rotate stably at a certain speed, then, sampling was done at the rate of 140 Hz during 6 seconds and four groups of data were recorded. They were the rotor torque, thrust, and pitch and roll moments respectively. The rpm of the beam was recorded simultaneously. Sampling was also done before and after the rotor's running when the beam kept rotating stably, so as to get the fore and aft zeroes of the measurements at that velocity.

4 REDUCTION OF DATA

4.1 Typical Sampled Data

Four typical groups of samlped data of rotor thrust and torque are shown in Fig.4. The presence of severe fluctuations of thrust and torque are obvious in Fig.4b and 4d. It is also seen that there exist preiodicities in the thrust and torque fluctuations.

4.2 Mean Values

For each test point, each group of the sampled data were alone averaged over the sampling duration, and the correspondent mean values of the fore and aft zeroes were compared with each other to examine the zero drift of the system during the time of each test run. It was found that they shew good repeatability. The average value of each pair of the fore and aft zeroes was used as the mean zeroes and was substracted from the corresponding mean value sampled when the rotor was running, so as to obtain the mean value of rotor torque or thrust or pitch or roll moment at that velocity.

It should be noted that the effects of the centrifugal force due to the rotation of the beam on the measurements would be eliminated by substracting the average zeroes measured when the beam is rotating. However, a rotor disc tilt exists when both of the beam and the rotor are rotating due to a Coriolis moment acting on the centrally articulated blades. As a result,measured thrusts (T_m) are slightly less than the real values (T_r). The difference can be calculated as

longitudial tilt angle $\beta_{1c}=\omega/\Omega$

lateral tilt angle $\beta_{1s}=\beta_{1c}/8\gamma$ (γ is blade Lock number)

The real thrust should be

$$T_r=\frac{T_m}{\cos\beta_{1c}\ \cos\beta_{1s}}$$

This correction is included in the program of data reduction, and the results shew that the tilt angle of rotor disk was small (Fig.5) because the beam rate was very low.

The mean values for each velocity were reduced to dimensionless quantities with reference to the corresponding mean values measured in hover, and are presented as functions of the dimensionless velocity (V/v_h).

4.3 Fluctuations

For each velocity, the mean square deviations of each group of the sampled data were calculated.

The fore and aft zeroes were plotted as the functions of the dimensionless velocity($V/\Omega R$) (Fig.6 shows a typical graph). It is found that the mean square deviations of each group of the zeroes,which were caused by the mechanical viberation and the electrical interference in the system, are very small compared with the corresponding mean values (normally$<1\%$) and increase with the velocity linearly. For each test point, the mean square deviations of each group of the zeroes were substracted from the mean square deviation of the corresponding group of data sampled when the rotor was running, so as to obtain the net deviations of each group which represented the fluctuations of rotor torque, thrust, pitch and roll moments respectively. The net deviations were reduced to percentages of the corresponding mean values, and are presented as functions of the dimensionless velocity (V/v_h). The frequencies of the fluctuations were also analyzed through FFT, and two typical power spectra of rotor thrust and torque are shown in Fig.7a and 7b.

5 RESULTS AND DISCUSSION

5.1 Operation States of a Helicopter Rotor in Vertical Descent

The mean values of rotor torque, thrust, and pitch and roll moments are shown in Fig.8a and 8b as functions of dimensionless velocity (V/v_h). The curves of torque and thrust reflect the transition proceeding from the normal-propeller state through the vortex-ring state toward the windmill-brake state. The increase in torque indicates the beginning of the vortex-ring state (V/v_h=0.4), and the loss in thrust indicates the most turbulent region in vortex-ring state ($0.6<V/v_h<0.8$). On the other hand, the mean pitch and roll moments almost keep the same values as the velocity varies, except a slight variation due to the tilt of the rotor disc.

The fluctuations are demonstrated in Fig.8c and 8d. It is seen that the fluctuations rises remarkabaly as the rotor falls into the vortex-ring state, peaks at three-quarters of the hover induced velocity. Then, with further increasing of the descent velocity, the fluctuations go down as the rotor moves into the windmill-brake state. According to the power spectra (Fig.7), the period of the thrust fluctuation is 0.3-0.6 second, whereas the period of the torque fluctuation is about 3.7 seconds.

5.2 The Effecte of Disk Loading (Fig.9)

It is seen from Fig.9 that, for a given dimensionless rate of descent, the torque fluctuation of the rotor with lower disk loading is larger than that of the rotor with higher disc loading, whereas the thrust fluctuation appeares to be independent of the disc loading.

5.3 The Effects of Blade Twist (Fig.10)

Fig.10 shows that, the thrust drop of the rotor with -5.5° blade twist is larger than that of the rotor with -9.22° blade twist within the vortex-ring state, whereas the thrust and torque fluctuations seems to be almost the same for different blade twists.

5.4 The Effects of Fuselage (Fig.11)

As shown in Fig.11a and 11b, the presence of the model fuselage gives a similar effect on the mean thrust and torque to the "ground effect". No effect on the thrust and torque fluctuation is found.

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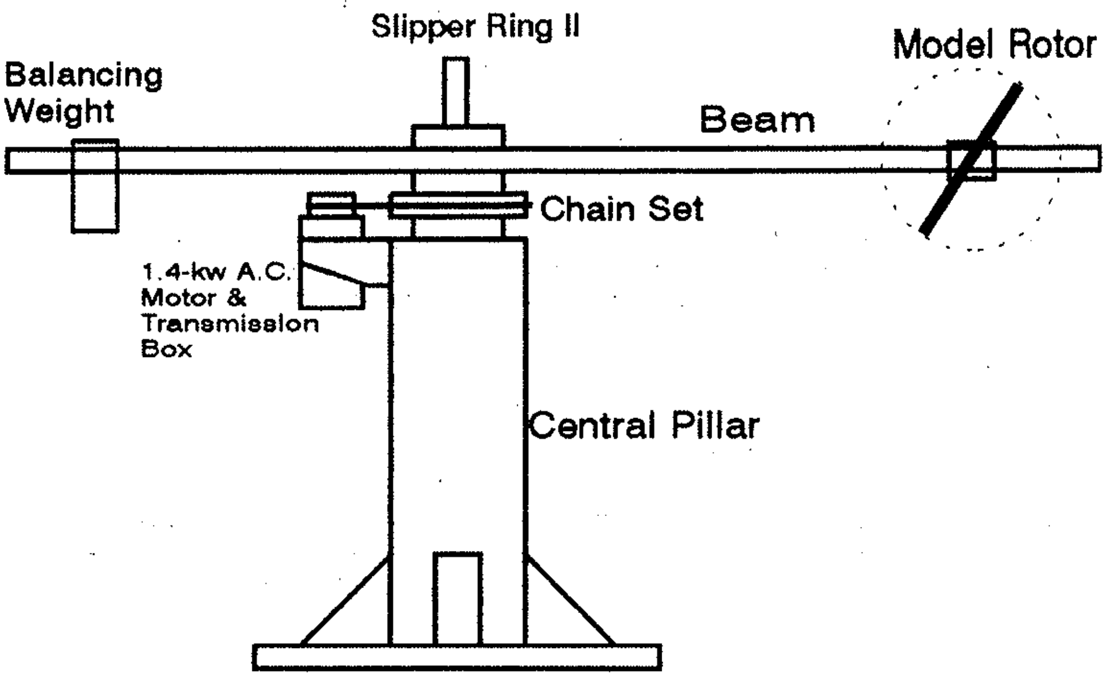


Fig.1 The Whirling Beam

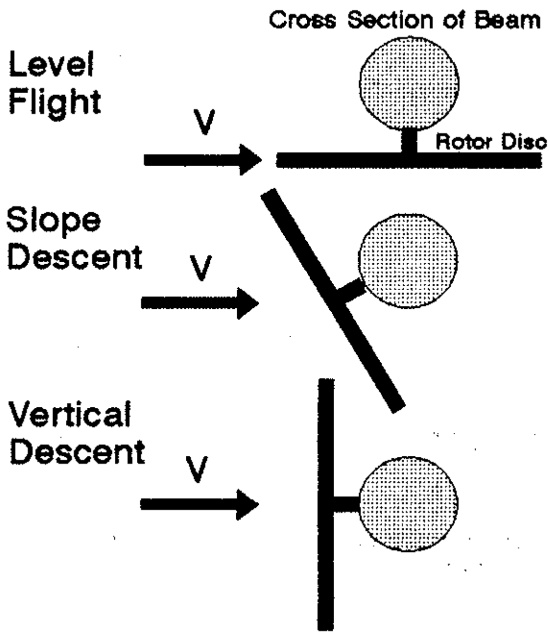


Fig.2 Orientations of the Rotor Axis and Corresponding Flight Conditions

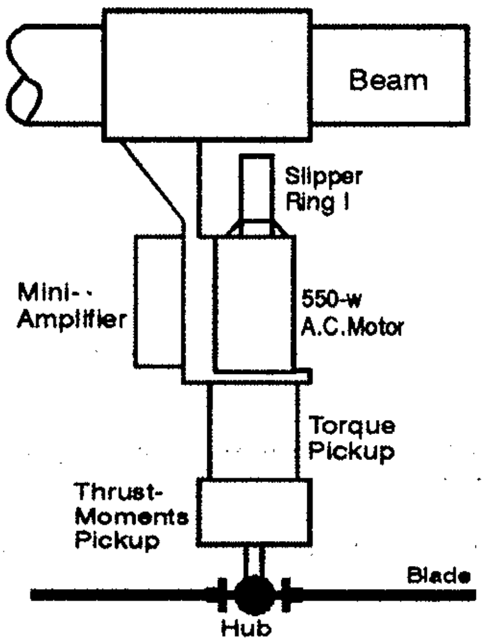
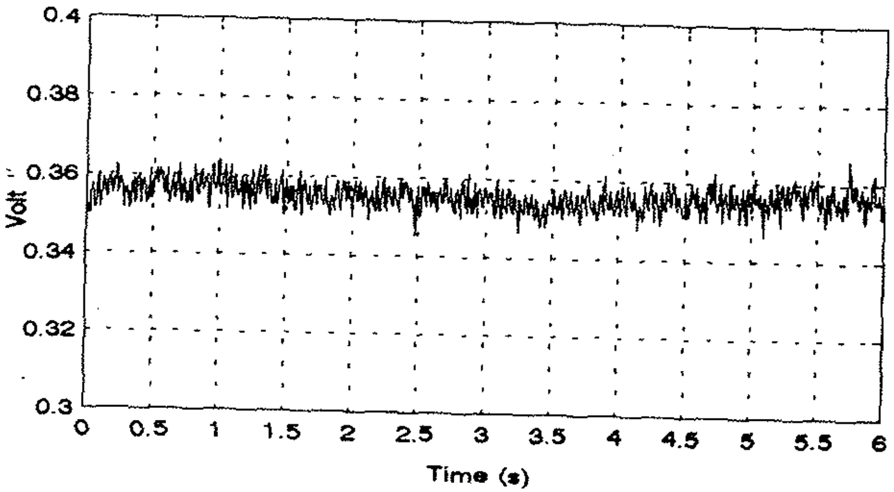
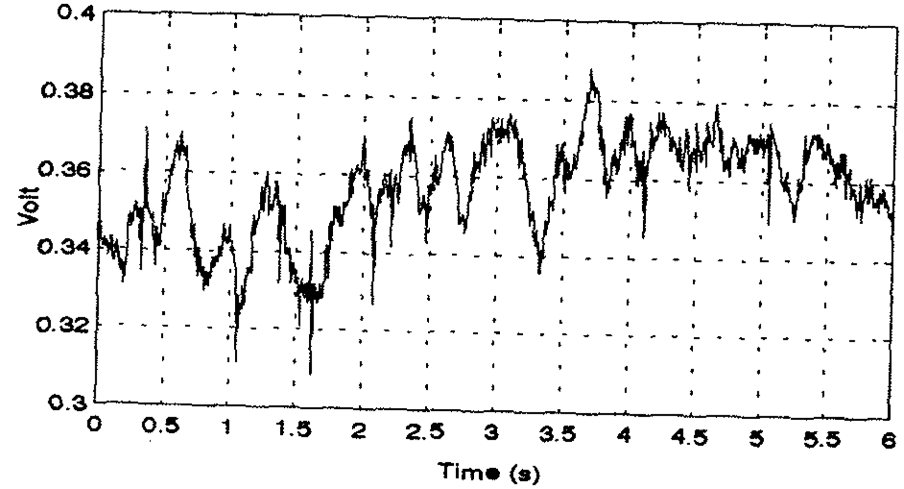


Fig.3 Rotor System



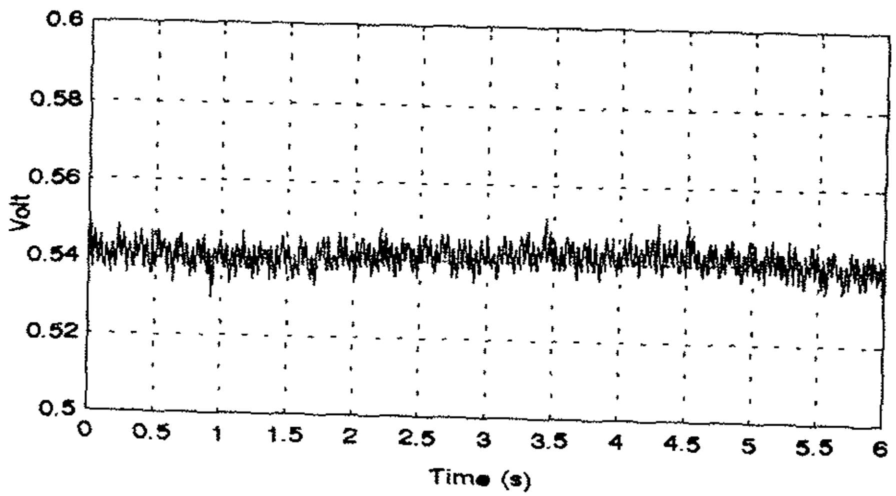
Average Value = 0.355, Mean Square Deviation = 0.00302

(a) Thrust in Hover



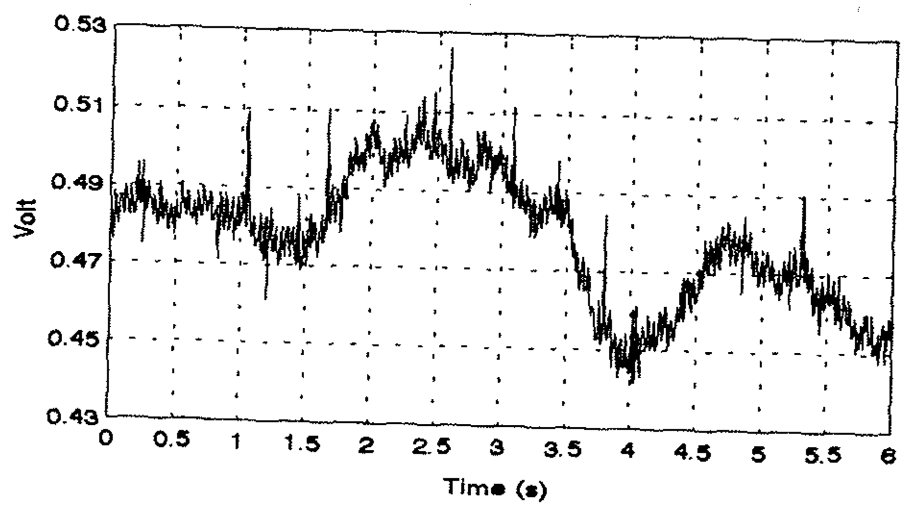
Average Value = 0.357, Mean Square Deviation = 0.0132

(b) Thrust in Descent (V/v_h=0.75)



Average Value = 0.541, Mean Square Deviation = 0.00329

(c) Torque in Hover



Average Value = 0.478, Mean Square Deviation = 0.0161

(d) Torque in Descent (V/v_h=0.75)

Fig.4 Typical Sampled Data ($\theta_{0.7}$=10°, Blade Set No.3, without Fuselage)

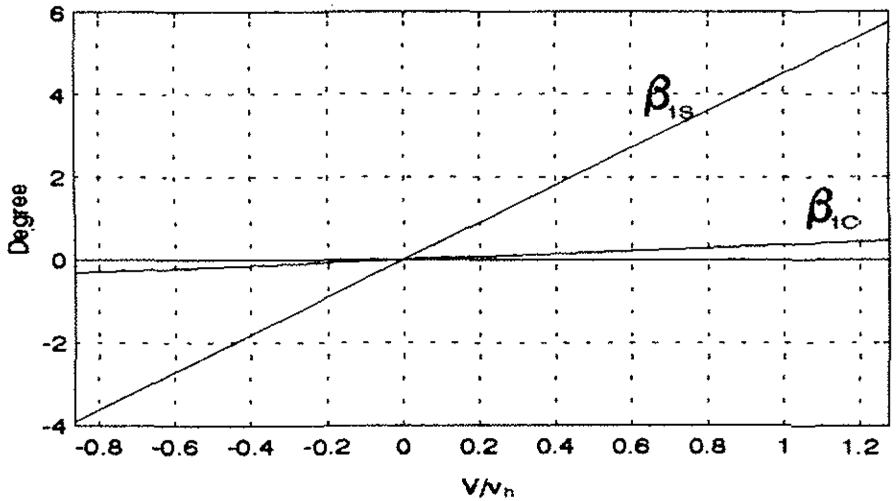


Fig.5 Tilt Angle Of Rotor Disc (Blade Set No.3)

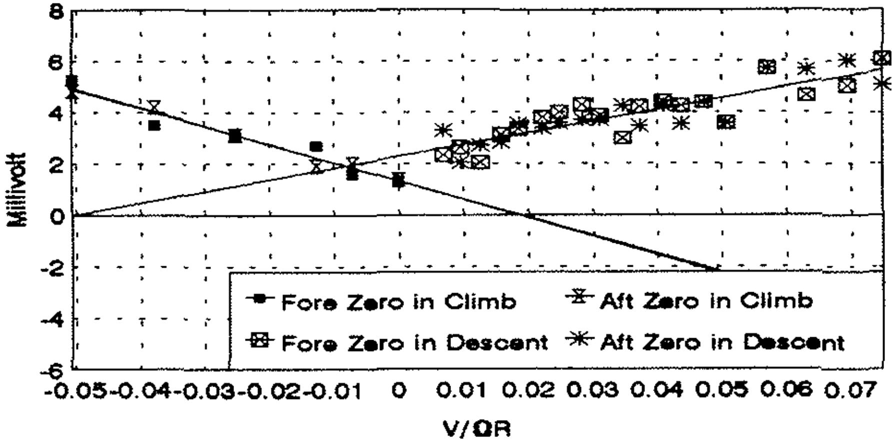
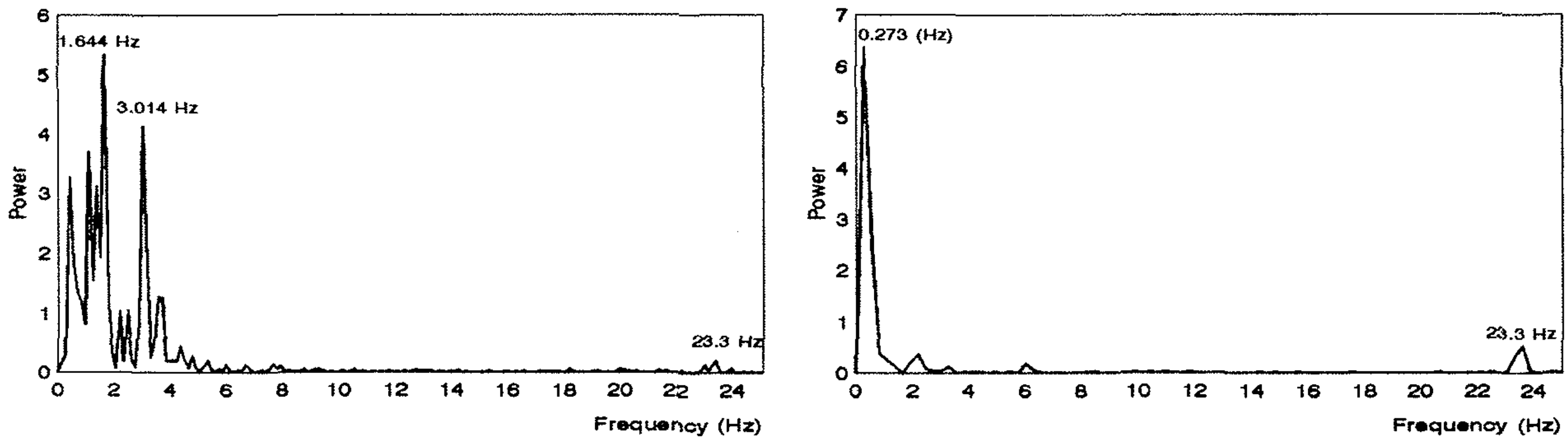


Fig.6 Mean Square Deviation of the Zeroes of Thrust as a Function of the Dimensionless Velocity
($\theta_{0.7}=10°$, Blade Set No.3, without Fuselage)



(a) Thrust

(b) Torque

Fig.7 Power Spectra ($V/v_h=0.75$, $\theta_{0.7}=10°$, Blade Set No.3, without Fuselage)

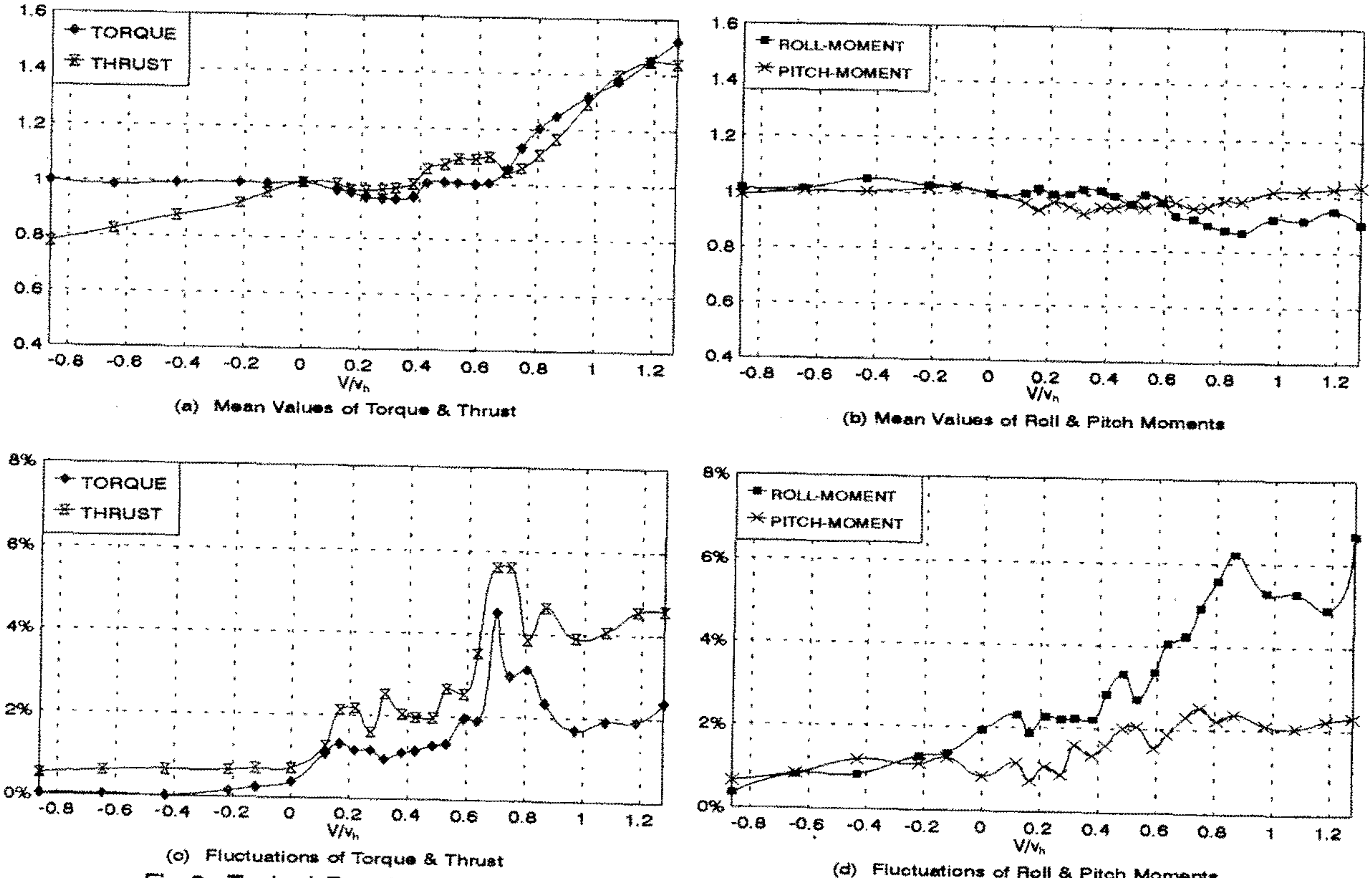


Fig.8 Typical Results of Data Reduction ($\theta_{0.7}$=10°,Blade Set No.3,without Fuselage)

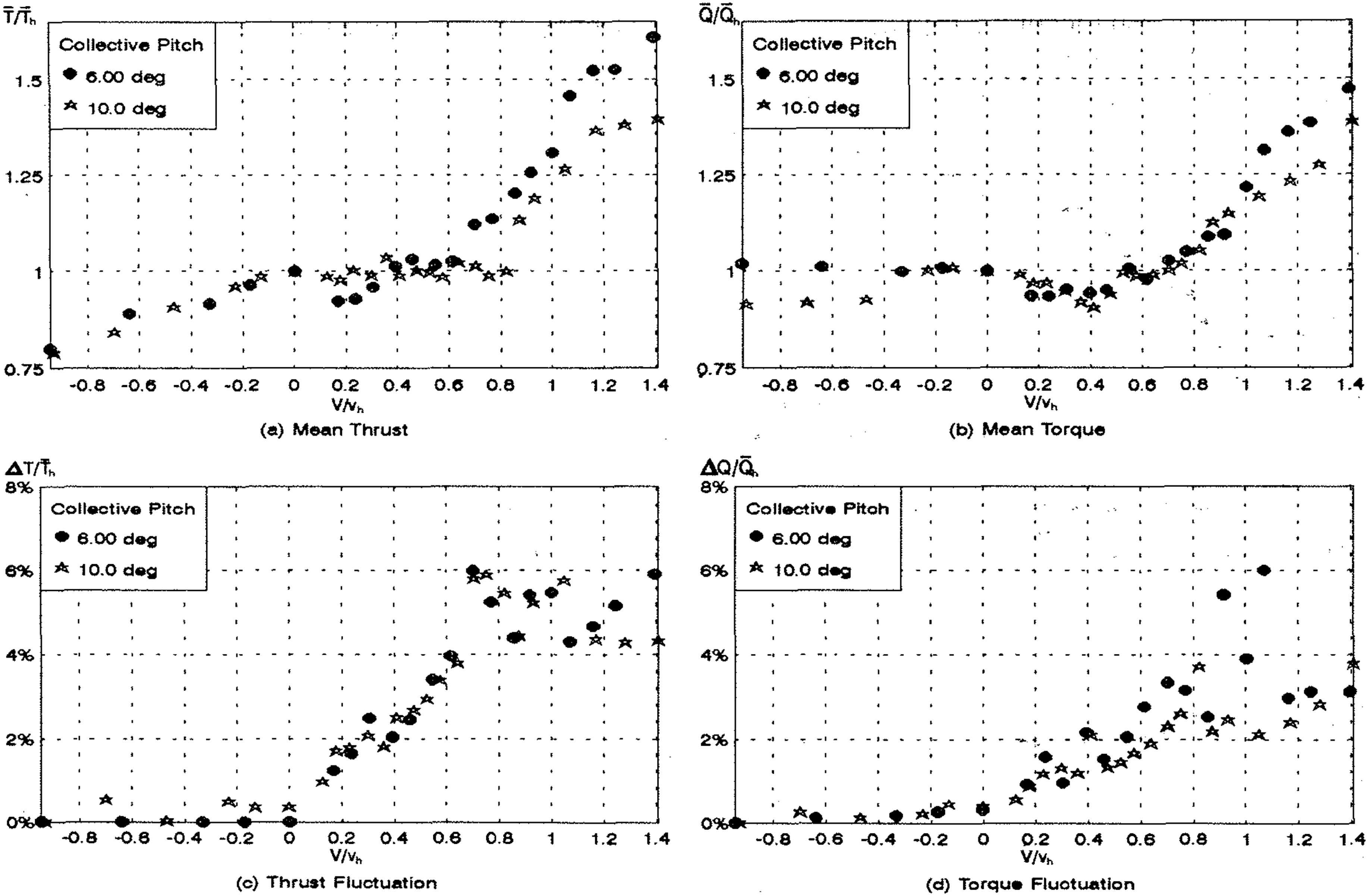


Fig.9 Effects of Disc Loading (Blade Set No.1,without Fuselage)

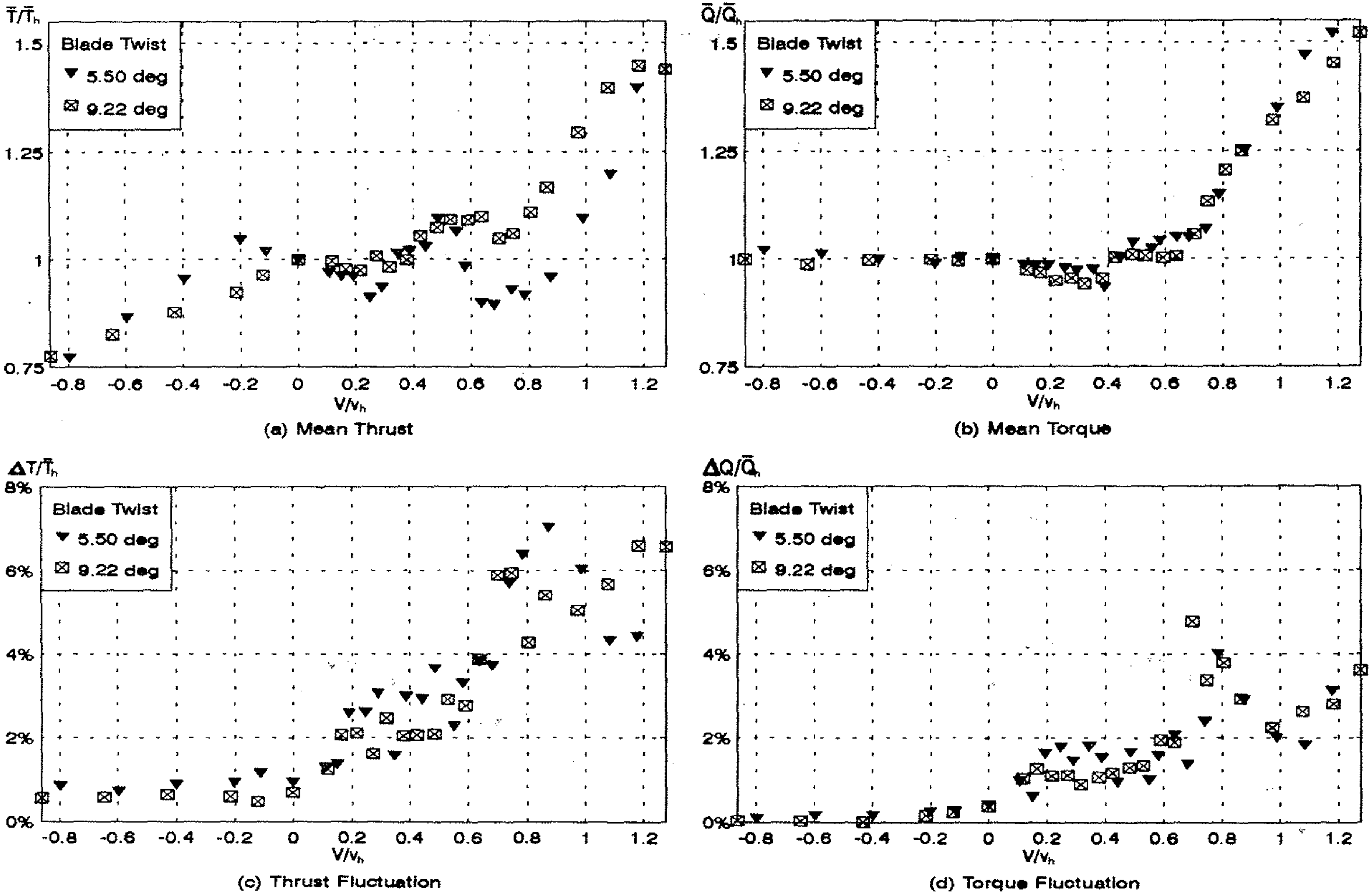


Fig.10 Effects of Blade Twist ($\theta_{0.7}=10°$,without Fuselage)

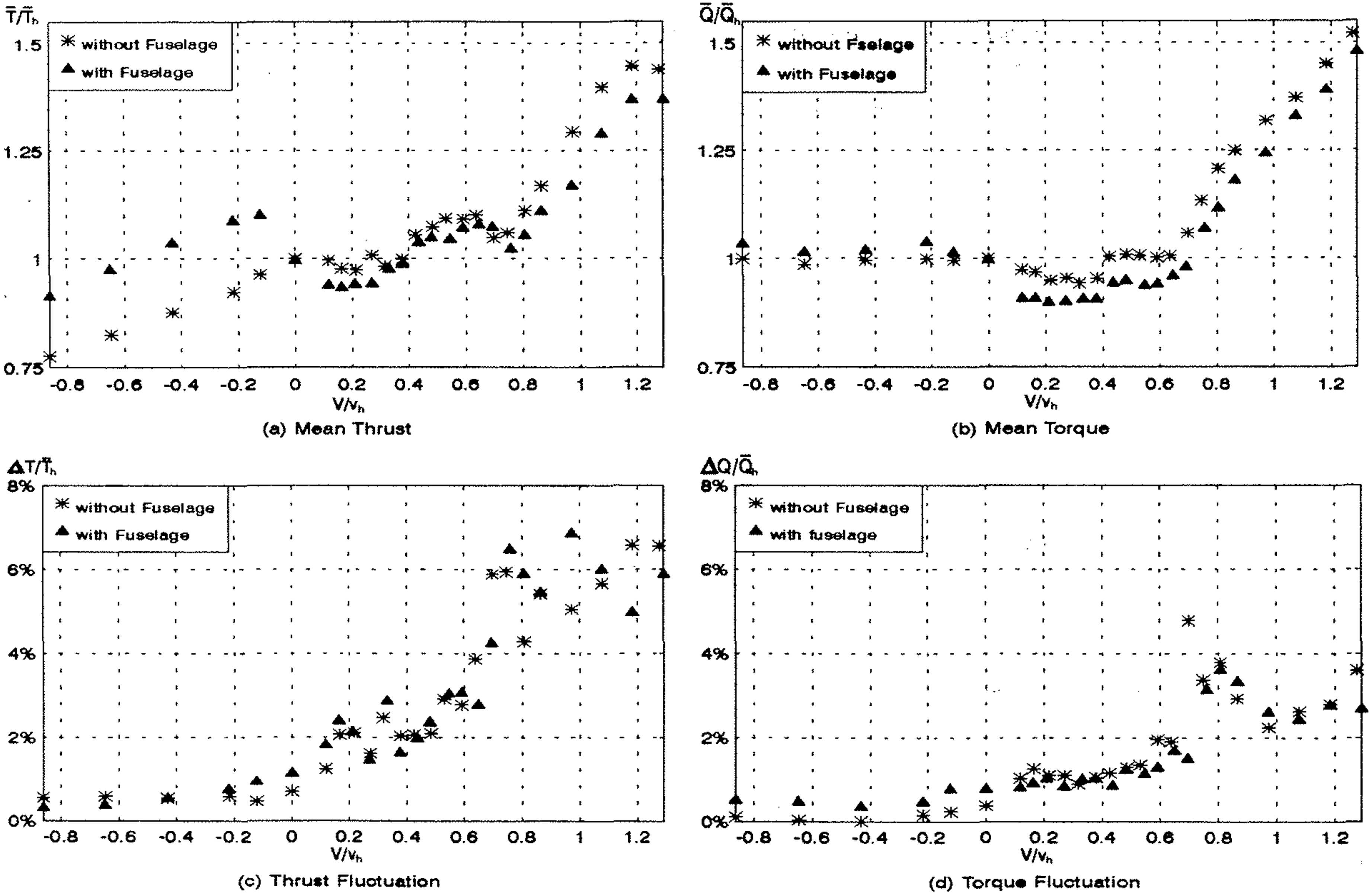


Fig.11 Effects of Fuselage ($\theta_{0.7}$=10 ,Blade Set No.3)