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THE MULTICHANNEL MOTIONAL STARK EFFECT DIAGNOSTIC ON TFTR

BY

F.M. LEVINTON

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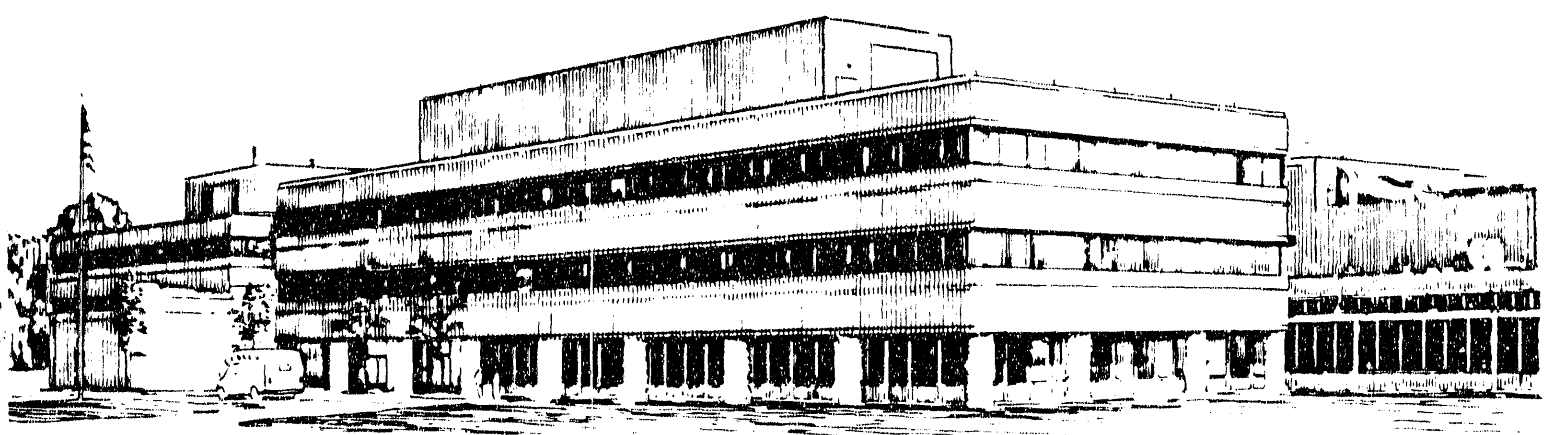
PPPL PRINCETON PLASMA PHYSICS LABORATORY



PRINCETON UNIVERSITY, PRINCETON, NEW JERSEY

The Multichannel Motional Stark Effect Diagnostic on TFTR

F. M. Levinton[1], Princeton Plasma Physics Laboratory,
Princeton University, Princeton, NJ 08543

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Abstract

Although the q profile plays a key role in theories of instabilities and plasma equilibrium, it has been quite difficult to measure until the recent development of the motional Stark effect (MSE) diagnostic. A multichannel motional Stark effect polarimeter system has recently been installed on the Tokamak Fusion Test Reactor (TFTR). The diagnostic can measure the magnetic field pitch angle ($\gamma_p = \tan^{-1}(\frac{B_p}{B_T})$) at ten radial locations. The doppler shifted D_α radiation from a TFTR heating beam is viewed near tangential to the toroidal magnetic field via a re-entrant front surface reflecting mirror. The field of view covers from inboard of the magnetic axis to near the outboard edge of the plasma with a radial spatial resolution of 3-5 cm. A high throughput f/2 optics system results in an uncertainty for γ_p of $\sim 0.1° - 0.2°$ with a time resolution of ~5-10 ms. Initial pitch angle profiles from TFTR have been obtained. The MSE data is consistent with the estimated magnetic axis position from external magnetic measurements and the q=1 radius is in good agreement with the inversion radius from the electron cyclotron emission temperature measurements.

[1]Permanent address: Fusion Physics & Technology, Inc. 3547 Voyager Street, Torrance, California 90503

I. Introduction

The current density profile and the safety factor $q(R)$ are essential in the theoretical modeling of plasma equilibrium, stability, and transport. Many phenomena, such as sawteeth, are not well understood due to the lack of consistent and detailed experimental data for $q(R)$. Also, with internal magnetic field data, a quantitative analysis can be made of the plasma equilibrium. This is particularly important for experiments where active control of the current profile, using rf, neutral beams, or bootstrap current is being pursued or planned for the future. To understand the effects of modifying the current density profile on stability, confinement, and transport, a credible means of determining the equilibrium is required. The MSE technique, developed on the PBX-M tokamak,[1] has been shown to provide the information necessary to determine the equilibrium. Important measurements of equilibrium[2,3] and stability[4] have been demonstrated with this technique on PBX-M and other devices using a scannable single channel diagnostic. With a multichannel system, such as on TFTR now, q(R) profiles are more reliable and readily available to help in understanding the plasma behavior and provide feedback for operation of the tokamak.

The motional Stark effect,[5] which arises from the electric field induced in the atom's rest frame due to its motion across the magnetic field ($\mathbf{E} = \mathbf{V}_{\mathbf{beam}} \times \mathbf{B}$) is used to measure the local magnetic field pitch angle. This is possible because the Stark effect causes both a wavelength splitting of several angstroms and polarization of the emitted radiation. When viewed transverse to the field the $\Delta m = 0$ transitions, or π components, are linearly polarized parallel to the electric field and the $\Delta m = \pm 1$ transitions, or σ components, are linearly polarized perpendicular to the electric field, and parallel to the magnetic field. It is the measure of the direction of the linearly polarized σ components that provides the basis of this magnetic field pitch angle diagnostic.

II. Apparatus

The diagnostic on TFTR views one of the deuterium neutral beams that is used for heating the plasma. The beam energy can be varied from 85 to 120 keV. Generally data has been taken at 95 keV. The deuterium Balmer-alpha transition, $n = 3 \rightarrow 2$, which is at 656.1 nm, is Doppler shifted about 4.0 nm towards the red with the viewing geometry on TFTR. A plan view of the layout is shown in Fig. 1. The collection optics and polarimeter view the plasma via a front surface reflecting aluminium mirror. The re-entrant mirror was necessary to provide a field of view of the plasma from inboard of the magnetic axis to near the outboard edge of the plasma. The optics material is fused silica to minimize radiation darkening and keep the system compatible with D-T operation which is planned for TFTR in the future. All the optics, including the polarimeter, are f/2 or better with a 10 cm clear aperture to maintain a high throughput for maximum light gathering capability. This allows for a time resolution of $\sim$ 5 ms while still maintaining good statistics for measurement of the magnetic field pitch angle. The light collected by the lens combination is imaged through the polarimeter onto a fiber optic array. The fiber holder consists of 27 slots or sight lines arranged on a curved focal plane. The curve has been calculated to bring the fibers to a focus at the intersection of each sight line with the neutral beam. Each slot contains six fibers, arranged with three vertical by two horizontal fibers. The fibers are 1000 micron core diameter and 1100 micron cladding diameter. The image size at the focus in the plasma is about 3 cm in the radial direction. Due to the view being near tangential to the toroidal field the radial resolution remains 3-5 cm in the plasma even though the neutral beam has a width of 20 cm. At present there are enough fiber and detectors for ten sight lines.

The fiber-optic bundle runs from the machine area through a penetration in the shielding wall to the "hot cell," which is an area that is accessible during machine operation. Here the fibers are separated into ten channels of six fibers each corresponding to ten spatial locations in the plasma. The optics/detector layout is shown in Fig. 2. The light from a group of fibers is collimated through a 0.6 nm FWHM interference filter before being focused onto the photocathode of a photomultiplier (PMT) detector. The filters are individually set for each channel corresponding to its Doppler shifted wavelength. Since the beam energy, and hence the Doppler shift, can be varied, the filter needs to be tunable. Also the measured polarization fraction is very sensitive to wavelength and needs to be set to the central σ-components. The filter is tuned by heating between 25 °C to 60 °C which shifts the passband of the filter. The shift is about 0.017 nm/°C. This allows a change of $\sim$ 0.6 nm which can cover a beam energy range of 90 − 115 keV. The detectors are Hamamatsu R943-02 with GaAs photocathodes that have a quantum efficiency of $\sim$ 13% at the relevant wavelength. The PMT output is then amplified before the signal is split into a 1 kHz low pass filter for measurement of the unmodulated part of the signal and three lock-in amplifiers for demodulation at the three reference frequencies from the photoelastic modulators (PEM). Finally the lock-in amplifier outputs are recorded with a waveform digitizer for computer analysis. The complete control and data acquisition of the diagnostic is done by a Micro-Vax II computer. This permits remote control and monitoring of the mirror shutter, voltage for detectors, and filter heaters.

The polarimeter used here is basically the same as that described in Levinton et al.[6] The size of the clear aperture on the PEM's has been increased to 10 cm with a corresponding decrease in the resonant frequency of the modulators from ~ 40 kHz to ~ 20 kHz. Another important difference in the polarimeter used here is the use of three reference frequencies instead of two in the previous design. This is because the mirror introduces a phase difference between the s-polarized light and p-polarized light which results in the conversion of linearly polarized light to elliptically polarized light. The polarimeter effect on the collected light can be calculated using Meuller matrices.[7] If the phase difference and reflectivity ratio between the s and p polarization from the mirror is δ and r_s respectively, the polarization fraction is p_f, the frequency of the modulators are ω_1 and ω_2, the drive amplitude on the modulators is A_1 and A_2 and assuming the mirror axis is horizontal then the resultant intensity, to highest order from the polarimeter is,

$$\begin{aligned} I_o &= I_i\{\tfrac{1}{4}[(1+r_s^2) + p_f(r_s^2-1)\cos(2\gamma_p)] \\ &- \tfrac{J_2(A_2)}{2\sqrt{2}}\cos(2\omega_2 t)[(r_s^2-1) + p_f(r_s^2+1)\cos(2\gamma_p)] \\ &- \tfrac{J_2(A_1)}{\sqrt{2}}\cos(2\omega_1 t)[p_f r_s \sin(2\gamma_p)\cos(\delta)] \\ &+ \tfrac{J_1(A_2)}{\sqrt{2}}\cos(\omega_2 t)[p_f r_s \sin(2\gamma_p)\sin(\delta)] \\ &+ \ldots \text{ higher harmonics}\}. \end{aligned} \tag{1}$$

The last two terms in Eq. (1) determine the phase difference from the mirror and together with the $J_2(A_2)$ term determines the magnetic field pitch angle.

Calibration of the diagnostic is a very important element to the successful implementation of this technique. The principle method for calibration consists of injection of a neutral beam into a gas filled torus. With known currents in the toroidal and equilibrium field (EF) coils the fields in the torus can be calculated to determine the local magnetic field pitch angle. The EF current can produce a variation in pitch angle comparable to that obtained from a plasma discharge. The calibration obtained this way includes all the effects that are present during normal operation such as Faraday rotation from the optics and window, the polarization projection factor,[6] and the polarization fraction.

III. Results

The multichannel MSE system on TFTR began operation during the fall 1991 run period. Initial shakedown and preliminary data has been obtained. The signal-to-noise of the data is very good with typical calculated pitch angles for several channels shown in Fig. 3. The relative uncertainty of the pitch angle is $\sim 0.1°$ with a time resolution of 50 ms in this example. The absolute error is somewhat larger due to systematic errors caused by coating of the mirror by the plasma, which caused the calibration results to vary with time as the deposited coating varied. This should be corrected for the next run period. The time evolution of the magnetic axis location and the axial safety factor q(0) are shown as a function of time in Fig. 4. The outward motion of the axis position between 1.5 and 2.0 s is due to the increasing major radius of the plasma from the preprogrammed formation. Also, the neutral beam heating of the plasma, which started at 1.5 s, increased β_θ and hence caused an increase of the Shafranov shift of the magnetic axis. Also shown in Fig. 4 is the calculated magnetic axis location from the external magnetics measurements which is in very good agreement with the MSE measurements. Both measurements have the same temporal behavior, but are offset by a couple of centimeters, which is near the absolute uncertainty of both measurements. The external magnetic measurement of the magnetic axis position is approximate due to profile effects that are not taken into account. While the plasma current is increasing between 1.5 and 2.0 s, the pitch angle profile is changing along with the q(R) profile. Profiles are shown in Fig. 5 at three times during the plasma evolution. At 1.55 s q(0) is just below 1 and is rapidly decreasing to a steady state value of 0.73. Over this time interval comparisons have been made with the electron cyclotron emission (ECE) measurements of the electron temperature. The ECE data shows sawteeth during the entire interval. The inversion radii at 1.55, 1.70, and 2.5 s are 2.63, 2.75, 2.86 m which is in good agreement with the q(R)=1 radii from the MSE data.

Systematic errors in the data have not been fully evaluated yet. However the preliminary data from the MSE diagnostic is showing good consistency with other measurements. The system has demonstrated both temporal resolution and relative uncertainties which will make the MSE measurements on TFTR very effective at investigating many important equilibrium, stability, and transport questions.

IV. Acknowledgments

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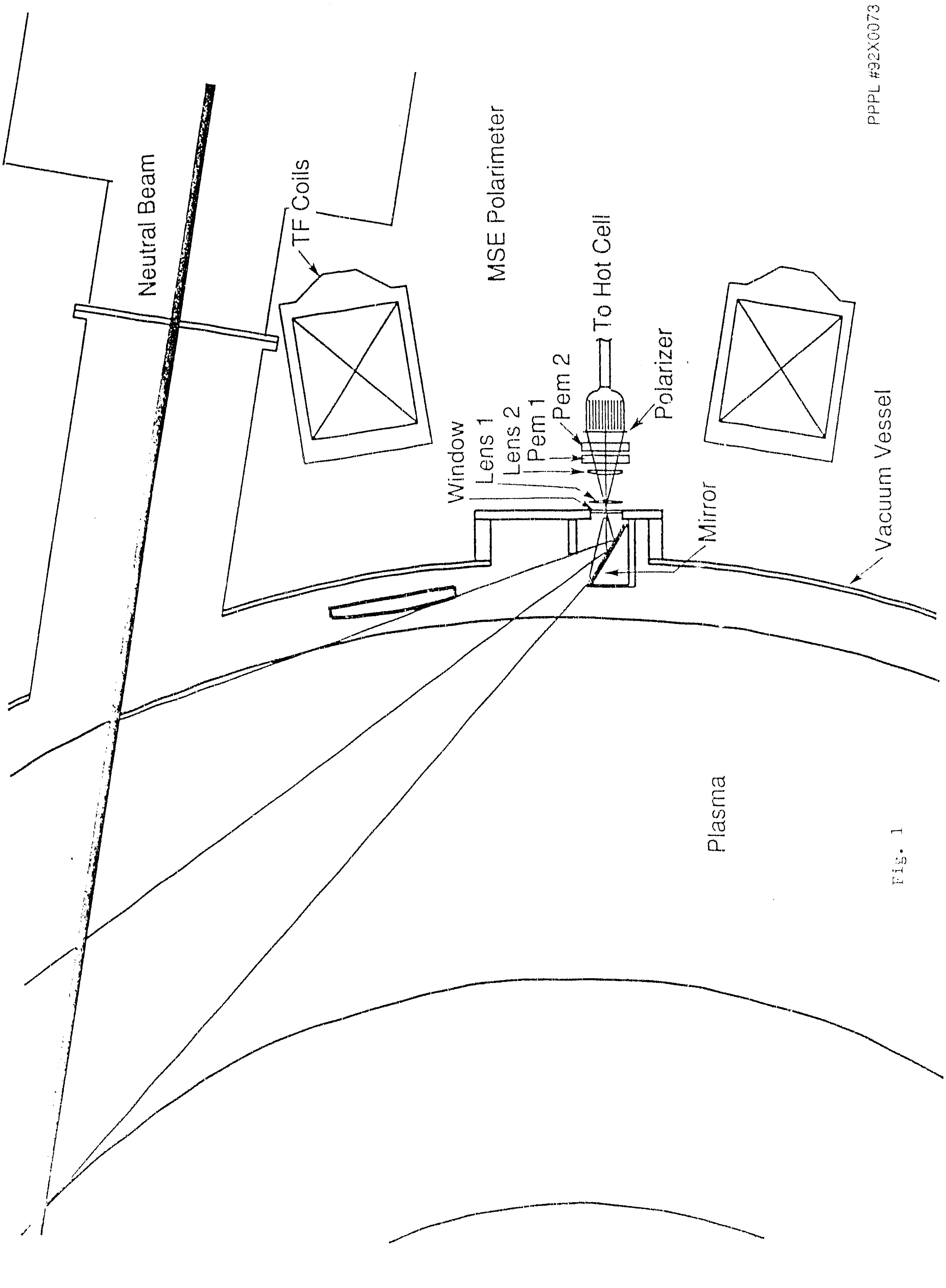
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TF Coils
MSE Polarimeter
To Hot Cell
Polarizer
Pem 2
Pem 1
Lens 2
Lens 1
Window
Mirror
Vacuum Vessel
Plasma

Fig. 1

MSE Detector/Electronics Layout (1 of 10 channels)

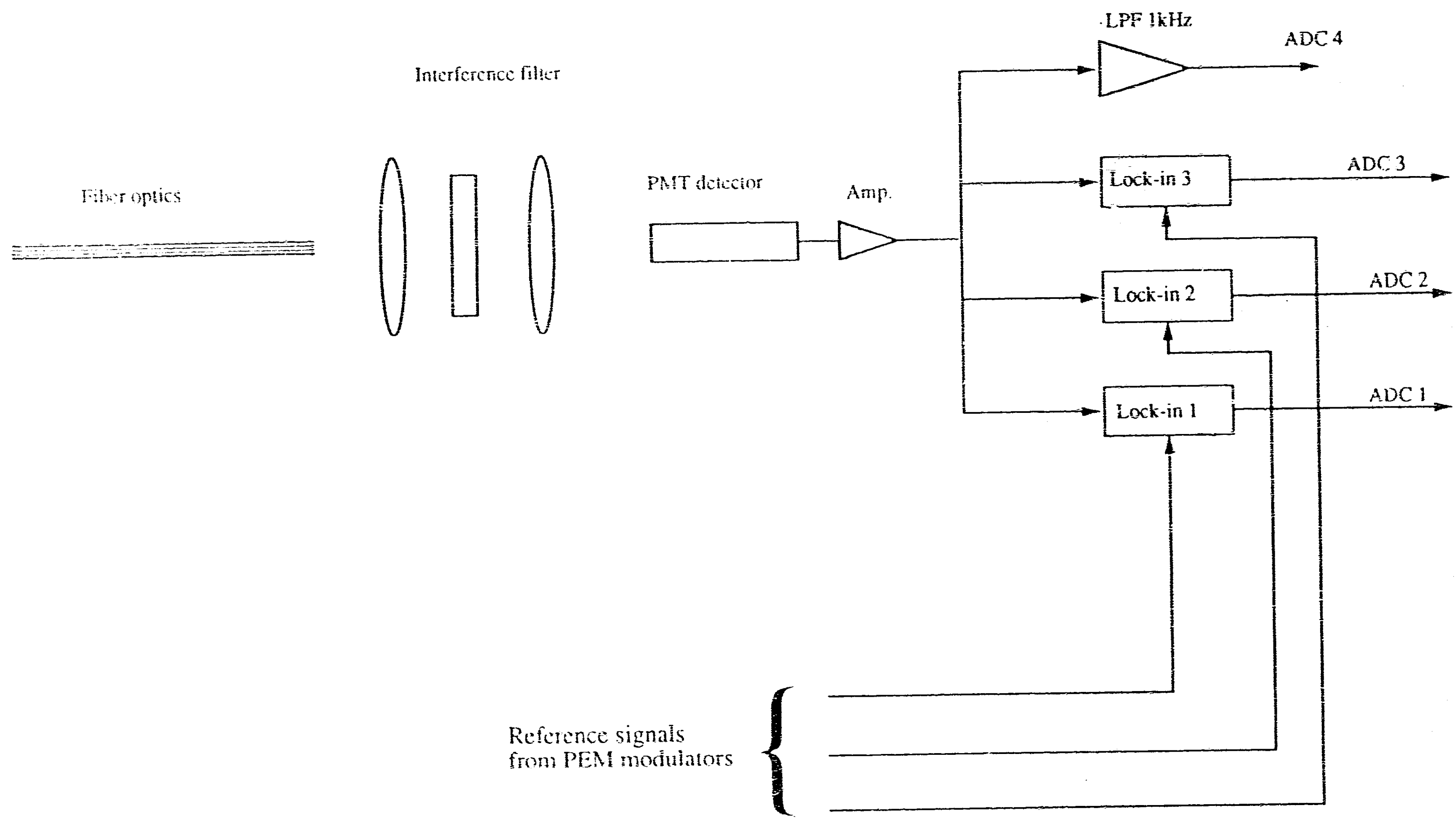

Fig. 2

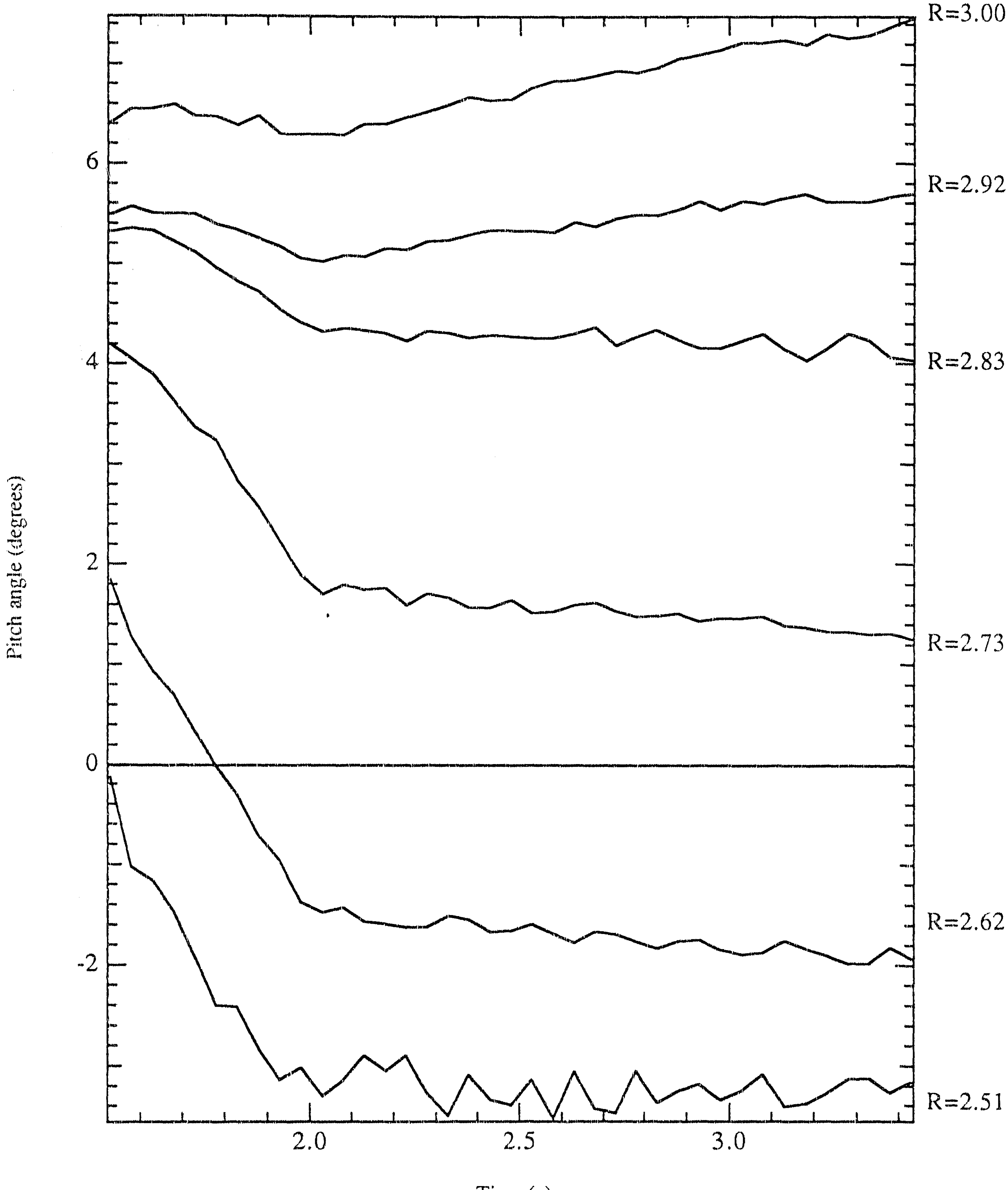
R=3.00
R=2.92
R=2.83
R=2.73
R=2.62
R=2.51
6
4
2
0
-2
Pitch angle (degrees)
2.0
2.5
3.0
Time (s)

Fig. 3

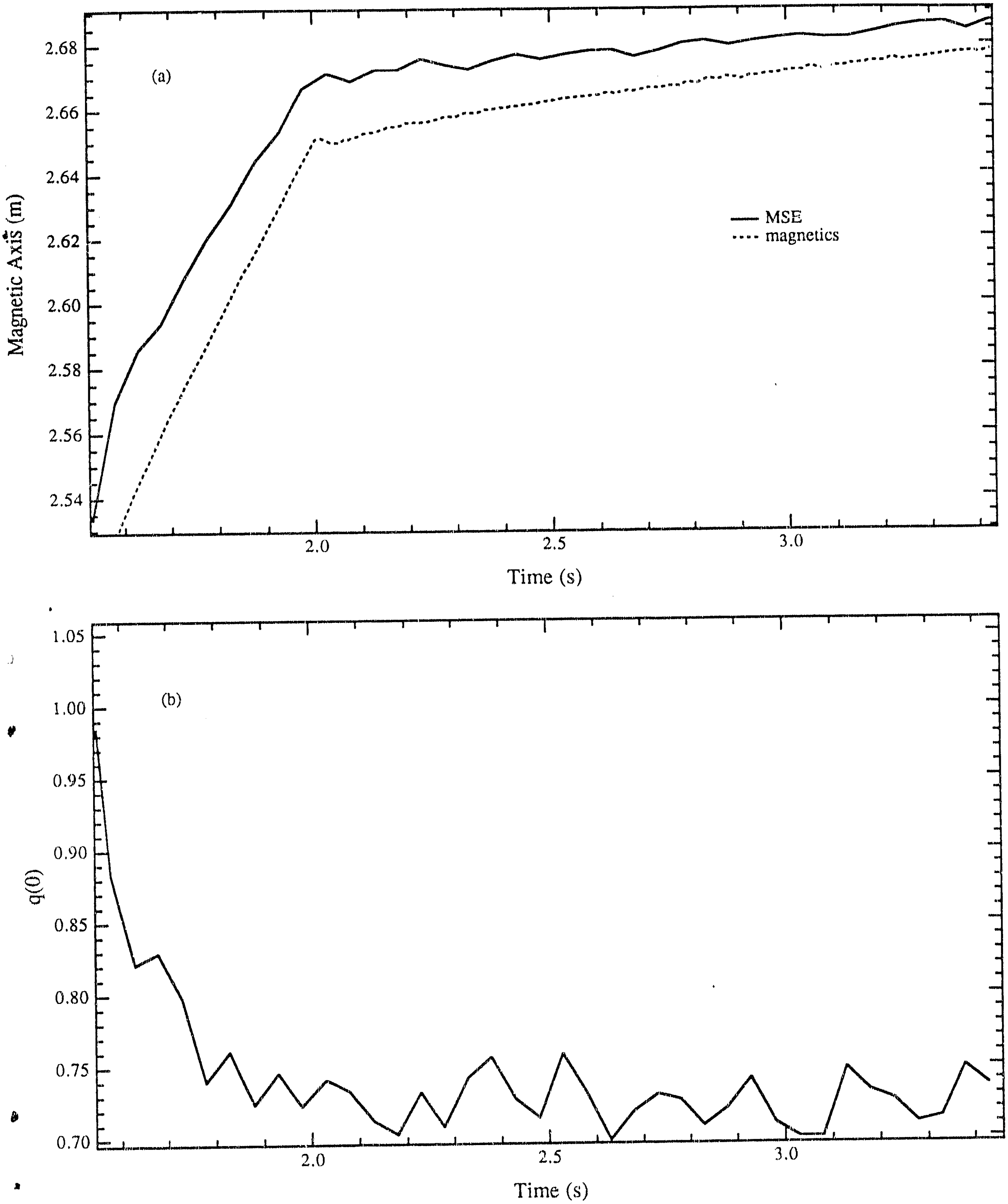
2.68
2.66
2.64
2.62
2.60
2.58
2.56
2.54
Magnetic Axis (m)
(a)
MSE
magnetics
2.0
2.5
3.0
Time (s)
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
q(0)
(b)
2.0
2.5
3.0
Time (s)

Fig. 4

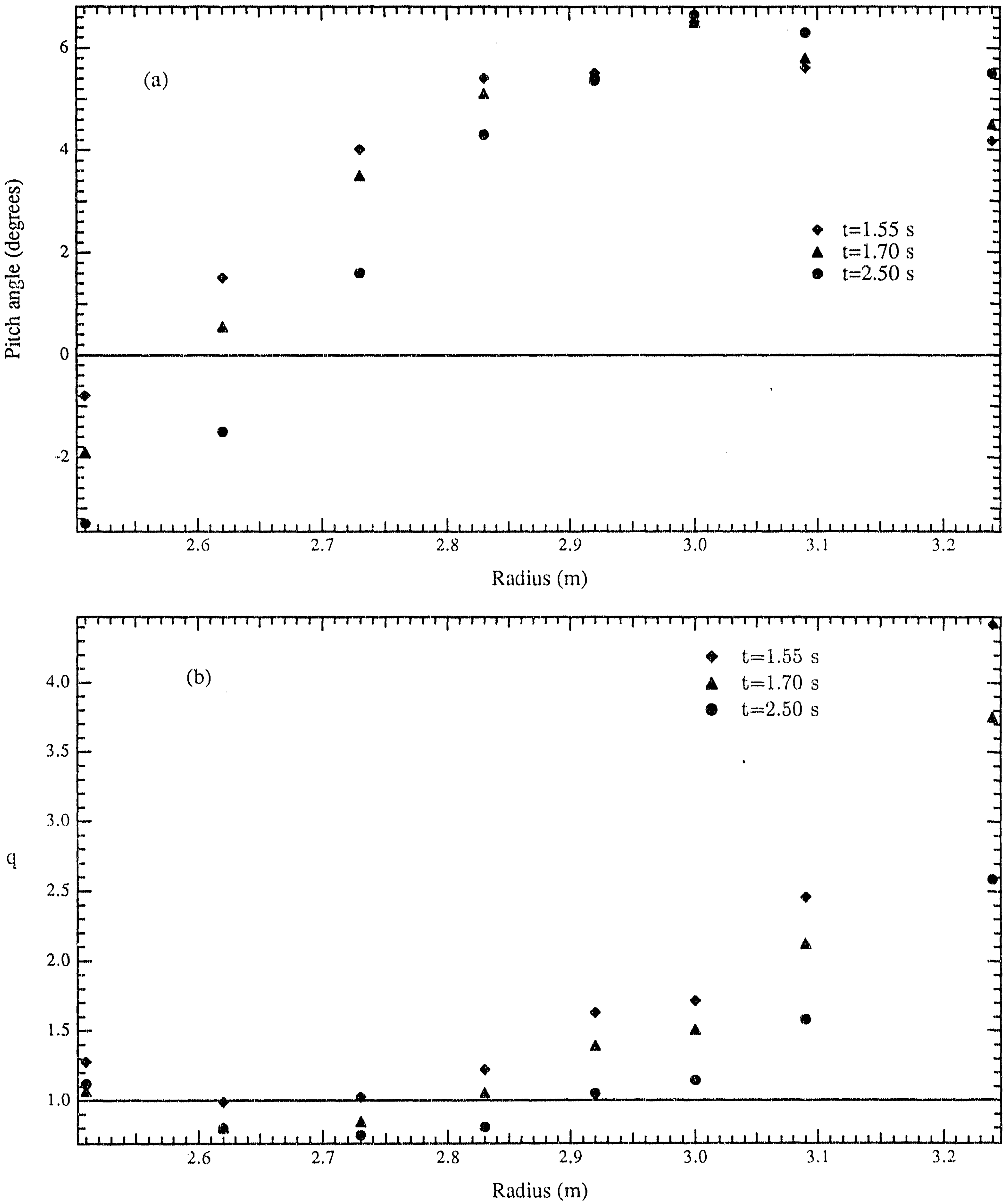
(a)
Pitch angle (degrees)
6
4
2
0
-2
2.6
2.7
2.8
2.9
3.0
3.1
3.2
Radius (m)
t=1.55 s
t=1.70 s
t=2.50 s
(b)
q
4.0
3.5
3.0
2.5
2.0
1.5
1.0
2.6
2.7
2.8
2.9
3.0
3.1
3.2
Radius (m)
t=1.55 s
t=1.70 s
t=2.50 s

Fig. 5

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