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MELBOURNE, VICTORIA

Aero Propulsion Technical Memorandum 445

A MODIFIED LEAST SQUARES ESTIMATOR
FOR GAS TURBINE IDENTIFICATION

by

G.L. Merrington

Approved for public release

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**A MODIFIED LEAST SQUARES ESTIMATOR
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G.L. Merrington

SUMMARY

A simple estimator is proposed for use in extracting the spool dynamic characteristics of a gas turbine engine. It provides realistic estimates even when the input/output signals are contaminated by high levels of measurement noise. As a result, it has the potential to form the basis of a useful engine health monitoring tool.

Transfer function of Jet engine. Fault diagnosis



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CONTENTS

	<u>Page</u>
NOMENCLATURE	
1. INTRODUCTION	1
2. DYNAMIC HEALTH OF A GAS TURBINE ENGINE	2
3. ANALYSIS TECHNIQUE	3
3.1 Model Structure and Estimator Development	3
3.2 Modified Least Squares Estimator	6
4. RESULTS	7
4.1 Simple Lag Model	7
4.2 Predicted Spool Speed Profiles	9
4.3 Comparison of MLSE/LSE Performance	10
5. CONCLUSIONS	10
REFERENCES	11

FIGURES

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NOMENCLATURE

A	Model parameter	
B	Model parameter = $K_N \Delta t / t_N$	
K_N	Spool steady-state gain	%RPM/lb/s
N	Spool speed	%RPM
n	Number of sample points	
P	Pressure	PSI
S	Laplace operator	
t_N	Spool time constant	(s)
t	time	(s)
T	Temperature	K
u	Generalised input	
WF	Fuel flow	(lb/s)
WFE	Overfuelling	(lb/s)
WFSS	Steady State Fuel Flow	(lb/s)
y	Generalised output	
Y	Output vector	
e	Output error	
ξ	Output error vector	
θ	Parameter vector	
ψ	Vector of past measurements	
σ	Standard deviation	
Δ	Difference operator	

INTRODUCTION

Gas turbine engines in military combat aircraft operate in a non-steady state condition for an appreciable proportion of the mission time. This means that for aircraft equipped with an Engine Monitoring System (EMS), faults detected in-flight with an on-board computer will most probably have to be diagnosed from transient engine data records. Current monitoring systems enable some important engine parameters such as spool speeds, selected engine pressures, temperatures and perhaps a final nozzle area, to be automatically recorded under such conditions. However, the number of measurands is normally insufficient to allow fault diagnosis to the required component and/or module except in a few isolated examples.

Most currently available fault diagnostic procedures are not suitable for analysing transient engine data and therefore there is a requirement to devise new methods for this purpose. A method is outlined in Reference 1 whereby changes in the spool dynamic characteristics of an engine, namely time constants and steady-state gains, can be correlated with known engine faults to form appropriate fault signatures. For such a concept to be useful as a diagnostic tool, a parameter estimator technique is required which is capable of extracting the necessary spool dynamic information from the available EMS records.

In this Technical Memorandum, a simple method is outlined for obtaining this information from small engine transients conducted under sea level static (SLS) test conditions. In developing this technique the following aspects were considered important:

- a. the method should be simple to implement,
- b. it should be capable of being accommodated in a small computer for eventual inclusion in a mobile test facility,
- c. it should provide useful estimates of the spool dynamics from normal closed-loop engine transients, that is accelerations and decelerations derived from simple throttle movements, and
- d. be capable of providing this information from EMS data contaminated with the usual amounts of measurement noise.

A technique with these capabilities could form the basis of an important tool to assess the dynamic performance or health of an engine by monitoring changes in the dynamic characteristics in the presence of faults.

2. DYNAMIC HEALTH OF A GAS TURBINE ENGINE

The transient response of a gas turbine is governed by the engine Fuel Control Unit (FCU), which contains control functions to enable the engine to be accelerated and decelerated within the aircraft operating envelope without transgressing the well defined limit boundaries based on flow instability and material strength considerations. A necessary prerequisite for successful engine operation is that the controller dynamics are suitably matched to those of the engine which in turn, ensures that the desired thrust levels are attained rapidly and without excessive transient overshoots.

Engine changes arising from faults, repairs, modifications, degraded components and general ageing effects can modify the effective spool dynamic characteristics and therefore change the resultant transient response of an engine. A technique that is capable of monitoring these effects by extracting the information from normal input/output (fuel/spool speed) measurements could provide the basis of a valuable maintenance aid. In the event that changes in the effective dynamic characteristics can be suitably correlated with known engine mechanical state conditions or faults, then the method has further appeal in that some abnormalities have the potential to be diagnosed without the need for additional instrumentation or specialised tests, Reference 1.

Introduction of the technique is reliant upon the EMS having sufficient capability to record the relevant data at adequate sampling rates and without excessive levels of measurement noise. For gas turbines, the characteristic frequencies based on the spool time constant, are less than 5 Hz and therefore a sampling rate of > 10 Hz is required to reduce possible aliasing effects. The advent of compact digital computer based data acquisition systems means that these data rates, combined with adequate memory, can be achieved with a relatively inexpensive system. Moreover, some current generation aircraft already have EMS which satisfy these minimum requirements.

In the following section, a suitable parameter estimator technique, which is capable of extracting the necessary dynamic information from noisy transient engine measurements, is outlined.

3. ANALYSIS TECHNIQUE

3.1 Model Structure and Estimator Development

The spool speed-fuel response of a gas turbine can be represented by a non-linear function of the form

$$N = f(WF, t_N, K_N, P, T)$$

In the vicinity of a steady-state set point, the response is closely approximated by a simple-lag model, Fig 1. This can be conveniently expressed in the form

$$\frac{\Delta N}{\Delta WF} = \frac{K_N}{1 + t_N S} \quad (3.1)$$

where ΔN = small change in spool speed
 ΔWF = small change in fuel flow
 K_N = spool speed/fuel steady-state gain
 t_N = spool time constant
 S = Laplace operator

Equation 3.1 can be reformulated in terms of the overfuelling (WFE = WF - WFSS) to yield an equation of the form

$$\Delta N = \frac{K_N}{t_N S} \Delta WFE \quad (3.2)$$

Equation 3.2 then becomes in discrete time

$$N_t = N_{t-1} + \frac{K_N \Delta t}{t_N} WFE_{t-1}$$

$$\text{or } N_t = A N_{t-1} + B WFE_{t-1} \quad (3.3)$$

$$\text{where } A = 1.0 \text{ and } B = \frac{K_N \Delta t}{t_N}$$

Equation (3.3) is linear in the parameters and is therefore suitable for regression analysis. For convenience, Eq (3.3) can be rearranged in terms of generalised inputs/outputs u and y , respectively

$$y_t = A y_{t-1} + B u_{t-1} + \epsilon(t) \quad (3.4)$$

where y_t is the observed output at time t
 u_t is the observed input at time t
 $\epsilon(t)$ is the output error

or more generally

$$y_t + A_1 y_{t-1} + A_2 y_{t-2} + \dots = B_1 u_{t-1} + B_2 u_{t-2} \dots + \epsilon(t)$$

which in vector notation reduces to

$$Y_t = \theta^T \psi(t) + \xi(t)$$

where $\psi(t) = (-y_{t-1} \dots -y_{t-n}, u_{t-1} \dots u_{t-m})$

and $\theta^T = (A_1 \dots A_n, B_1 \dots B_m)$

The simplest form of estimator is the Least Squares Estimator (LSE) Reference 2. It is attractive because the basic algorithm is simple to implement but it has the disadvantage that it is known to give asymptotically biased parameter estimates in the presence of measurement noise, even for very large data samples (References 2, 3). Notwithstanding this the LSE was selected because of its simplicity and in the knowledge that some residual bias errors could be tolerated in the present application provided the levels of bias in the fault and no-fault cases are consistent. That is, provided the difference between the fault and no-fault parameter estimates is of greater importance than the accuracy of the individual estimates.

The LSE parameter estimates are obtained by minimising the sum of the squares of the output errors

$$\left| Y_t - \theta^T \psi(t) \right|^2$$

or in terms of equation (3.4)

$$\sum_{t=1}^n \left| y_t - Ay_{t-1} - B u_{t-1} \right|^2 \quad (3.5)$$

Differentiating with respect to the parameters A and B gives

$$\frac{1}{n} \sum_{t=1}^n y_t y_{t-1} - \frac{1}{n} A \sum_{t=1}^n y_{t-1}^2 - \frac{1}{n} B \sum_{t=1}^n y_{t-1} u_{t-1} = 0$$

$$\frac{1}{n} \sum_{t=1}^n y_t u_{t-1} - \frac{1}{n} A \sum_{t=1}^n y_{t-1} u_{t-1} - \frac{1}{n} B \sum_{t=1}^n u_{t-1}^2 = 0$$

and therefore the parameter estimates A and B are given by

$$\begin{pmatrix} A \\ B \end{pmatrix} = \begin{pmatrix} \frac{1}{n} \sum_{t=1}^n y_{t-1}^2 & \frac{1}{n} \sum_{t=1}^n y_{t-1} u_{t-1} \\ \frac{1}{n} \sum_{t=1}^n y_{t-1} u_{t-1} & \frac{1}{n} \sum_{t=1}^n u_{t-1}^2 \end{pmatrix}^{-1} \begin{pmatrix} \frac{1}{n} \sum_{t=1}^n y_t y_{t-1} \\ \frac{1}{n} \sum_{t=1}^n y_t u_{t-1} \end{pmatrix}$$

In the deterministic case, the estimator yields asymptotically unbiased estimates provided $\epsilon(t)$ is uncorrelated, that is the parameter estimates are consistent for large data samples (Reference 2). If $\epsilon(t)$ is correlated, more complex estimators such as generalised least squares or maximum likelihood methods are required to give bias free estimates.

As alluded to previously, in many problems of practical interest the variables can only be observed in error because of the presence of measurement noise. The LSE yields asymptotically biased estimates of the parameters under these conditions where the magnitude of the bias error is a function of the signal to noise ratio (S/N). Consequently, at low signal to noise ratios the parameter estimates will be biased away from the true value even for very large data samples.

Small scale bias errors can be tolerated in some applications, for example when reconstructing the dependent variable from the noisy input variable. In these

circumstances, it can be shown that the results are usually unbiased provided the noise is stationary, Reference 3. This is supported by results obtained from a small turbojet at high engine speeds, Section 4. However, the LSE proved to be unsatisfactory at low engine speeds and the reason for this is that the S/N ratio of the input fuel signal deteriorated significantly at the lower engine speeds. Some of the deterioration can be attributed to the small scale of the engine and the difficulties associated with the mismatching of the experimental test rig fuel flow measuring devices across the full speed range of the engine. Further problems stem from the fact that most currently available parameter estimation techniques have been optimised for the case where the noise is primarily characterised on the output signal. In an attempt to overcome some of these difficulties a revised estimator was developed and will be subsequently referred to as the Modified Least Squares Estimator (MLSE).

3.2 Modified Least Squares Estimator

The MLSE utilises equation 3.3 as a filter to obtain improved estimates of the output speed profile. This is analogous to the use of the auxiliary model in the Instrumental Variable Technique (References 3, 4).

The LSE provides the initial parameter estimates for use in the MLSE. In particular, the LSE predicted parameter 'A' with good accuracy (<0.1%) but 'B' was biased. Therefore, keeping A constant, parameter B was incremented in predetermined steps until a minimum variance fit of the predicted output speed profile was obtained with the measured data. At each step, the model equation was employed to obtain updated estimates of the overfueLLing function. This numerical procedure is commonly referred to as 'hill-climbing'. Subsequent Monte Carlo simulation tests (Reference 1) indicate that the bias error in B is reduced to the same order as A, that is (<0.1%).

4. RESULTS

4.1 Simple-lag Model

In Section 3 it was shown that the simple lag model closely approximates the spool speed/fuel response of a gas turbine in the vicinity of a steady-state set point ($\Delta N < 5\%$). It is convenient to use this model to test the performance of the

estimator and thereby eliminate modelling errors or any process noise. For the deterministic, zero measurement noise case, the MLSE estimates agree precisely with those obtained for the LSE, Fig 2.

The addition of white measurement noise of similar magnitude to that observed during experimental tests on a small Cougar turbojet (Reference 5), gave rise to biased LSE estimates of the parameter B for the S/N ratios encountered at the lower engine speeds. For example, results presented in Fig 3 from one test indicate the estimated spool time constant, $t_N = 8.51$ exceeded the true value of $t_N = 0.8$ by an order of magnitude.

The most suitable reference for calculating the appropriate S/N ratio on the input fuel signal is the peak overfueling WFE_{max} , instead of the actual fuelling level. WFE_{max} represents the peak fuelling available to accelerate the spool to the new demanded speed and therefore is directly related to the transient performance of the engine. Therefore a suitable definition of the input S/N ratio is:

$$(S/N)_{WF} = 20 \log_{10} \left(\frac{WFE_{max}}{\sigma_{WF}} \right)$$

where σ_{WF} = standard deviation of the measurement noise. The results given in Reference 5 for the Cougar engine are reproduced here in Table 1.

N(% RPM)	WFE _{MAX} (lb/s)	σ_{WF} (lb/s)	(S/N) _{WF} (db)
68.5	.002	.0011	5.2
73.5	.0025	.0011	7.1
86.0	.005	.001	14.0
97.5	.006	.001	15.6

TABLE 1. Measurement Noise Levels for a Small Turbojet

At high engine speed for the Cougar, N = 97.5%, the approximate values of the spool dynamic characteristics are

$$K_N = 600 \% \text{ RPM/lb/s} \quad t_N = 0.4 \text{ s}$$

with noise estimates on the input/output signals of $\sigma_{WF} = .001$ and $\sigma_N = .2$, respectively. Typical measured results for a small closed loop acceleration at these high engine speeds are given in Fig 4. The corresponding results for a fuel step-response of a simple-lag model with these same dynamic characteristics when superimposed with white measurement noise are given in Fig 5. Parameter estimates obtained using the LSE and MLSE techniques for the data of Fig 5 are presented in Fig 6. The MLSE result more closely approximates the true value of the spool time constant, $t_N = 0.4$ and this is reflected in reduced parameter uncertainty and bias from ten similar tests, Table 2. It should be emphasized that the results of Table 2 are only intended as indicative estimates of the uncertainty and bias, prior to carrying out full scale Monte Carlo tests (Reference 1).

	TRUE VALUE	LSE	MLSE
K_N (% RPM/lb/s)	600	594.5 ± 38.6	594.5 ± 38.6
t_N (s)	0.4	0.36 ± 0.056	$0.4 \pm .05$
B (%RPM/lb/s)	46.875	52.02 ± 8.34	46.1 ± 6.78

TABLE 2. Parameter Estimates - Low Measurement Noise

The MLSE provides a good estimate of the time constant within a 2σ band of $\pm 12.5\%$. By comparison, the LSE predicts the time constant with a bias error of -10% within a 2σ band of $\pm 15.6\%$. It is apparent then that the MLSE yields improved estimates of the spool dynamics in the presence of moderate noise on the input fuel, $(S/N)_{WF} = 15.6$ db.

The exercise was repeated using representative values of the spool dynamics and measurement noise observed at a low engine speed on the Cougar, namely $N = 68.5\%$.

$$K_N = 1500 \text{ \% RPM/lb/s} \quad t_N = 0.8 \text{ s}$$

with noise levels of $\sigma_{WF} = .0011$, $\sigma_N = .075$. Parameter estimates obtained for the data in Fig 7, corresponding again to a simple-lag model with the above

characteristics and superimposed white measurement noise, are given for a series of ten tests in Table 3.

	TRUE VALUE	LSE	MLSE
K_N (%RPM/lb/s)	1500	1468.2 ± 172.78	1468.2 ± 172.78
t_N (s)	0.8	4.90 ± 4.48	0.90 ± 0.30
B (%RPM/lb/s)	58.59	11.44 ± 11.36	51.83 ± 16.04

TABLE 3. Parameter Estimates - High Measurement Noise

The MLSE predicts the time constant t_N with a bias error of + 12.50% within a 2σ uncertainty of $\pm 33.3\%$. The equivalent LSE values are poor by comparison, bias in t_N is + 513% within a 2σ uncertainty of $\pm 91.4\%$. It can be concluded then that the MLSE technique yields a much improved estimate at the low $(S/N)_{WP} = 5.2$ db encountered at the low engine speeds.

4.2 Predicted Spool Speed Profiles

Predicted spool speed profiles for the data given in Fig 5, corresponding to conditions prevailing at high Cougar engine speeds, agree well with the measurements using parameters derived either from the LSE, Fig 8(a) or from the MLSE, Fig 8(b). Conversely, results predicted from low engine speed data Fig 7, clearly indicates that the LSE estimate is poor, Fig 9(a) whereas the MLSE equivalent is acceptable, Fig 9(b).

The magnitude of the measurement noise, especially on the input signal, emerges as the most important factor in the overall performance of the estimator.

4.3 Comparison of MLSE/LSE Performance

The LSE is known to produce biased estimates in the presence of significant amounts of measurement noise, (Reference 2) and confirmed in the present results. However, as mentioned in Section 3.1, most currently available estimator techniques have been optimised for use where the measurement noise is predominantly

characterised on the output signal. This contrasts with the present application where the measurement noise is concentrated on the input signal. The discernible improvement in the predictive capability of the MLSE compared with that obtained from the LSE is clearly demonstrated in Figs 10 and 11 for $(S/N)_{WF} = (5.2 - 30)$ db. These results correspond to constant variance noise on the output speed signal. It is apparent then that the MLSE technique provides realistic estimates even when the input signal is contaminated with high levels of measurement noise $(S/N)_{WF} = 5.2$. As the $(S/N)_{WF}$ increases the LSE performance approaches that of the MLSE, as expected.

5. CONCLUSIONS

The MLSE technique is capable of extracting information on the spool dynamic characteristics from noisy measured data. In particular, the method appears to work well even when the measurement noise is primarily characterised on the input signal. This contrasts with most of the existing techniques which have been optimised for the case where the noise is characterised on the output signal.

The MLSE method produced consistently lower bias errors even in the presence of high measurement noise levels. For example, for the case where $(S/N)_{WF} = 5.2$, the bias in t_N could be reduced by over an order of magnitude compared with that obtained using the LSE.

The MLSE as described here, has been successfully applied to the problem of extracting the spool dynamic characteristics of a small turbojet without faults. It remains however to assess the capability of the estimator as a condition monitoring tool for use on operational engines. Therefore, it is proposed to carry out a series of tests on a current generation military turbofan engine, with and without embedded faults to assess the capability of the technique in an actual operational environment.

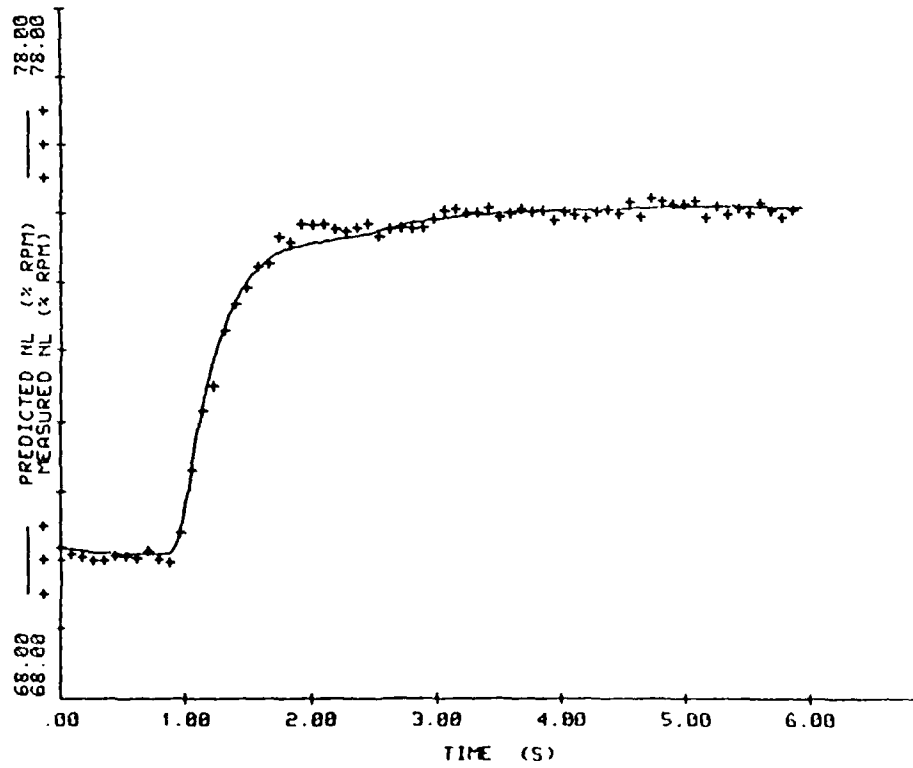


FIG. 1 COMPARISON OF SIMPLE LAG MODEL AND FULL THERMODYNAMIC TURBOFAN DATA

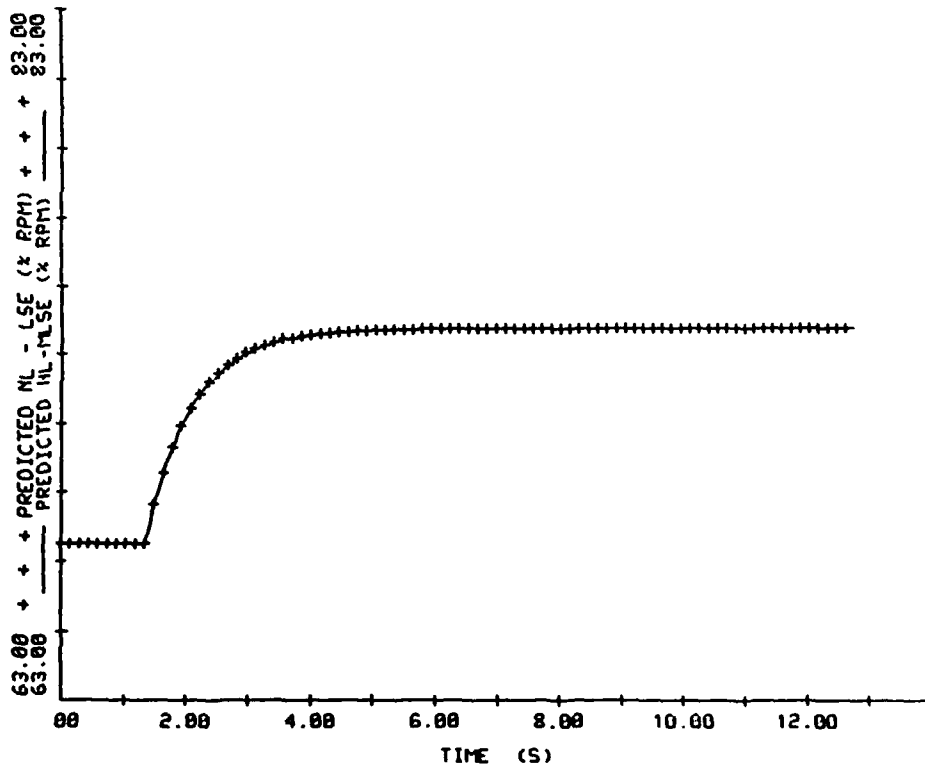


FIG. 2 MLSE/LSE COMPARISON WITH ZERO PROCESS NOISE AND ZERO MEASUREMENT NOISE

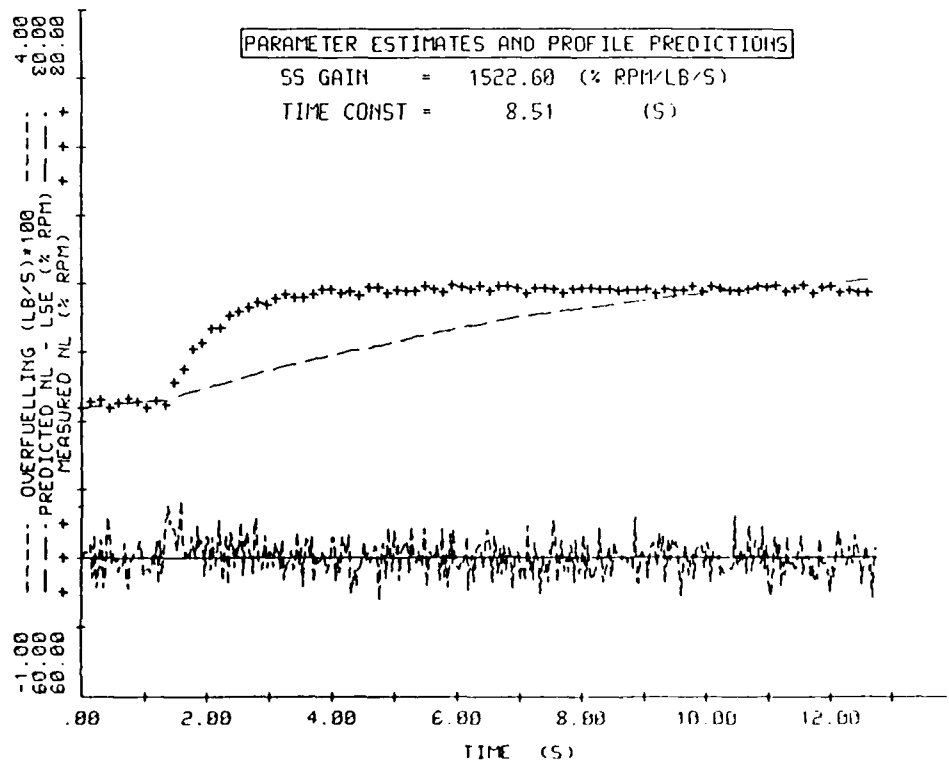


FIG. 3 LSE PREDICTIONS USING SIMULATED DATA WITH HIGH LEVELS OF MEASUREMENT NOISE

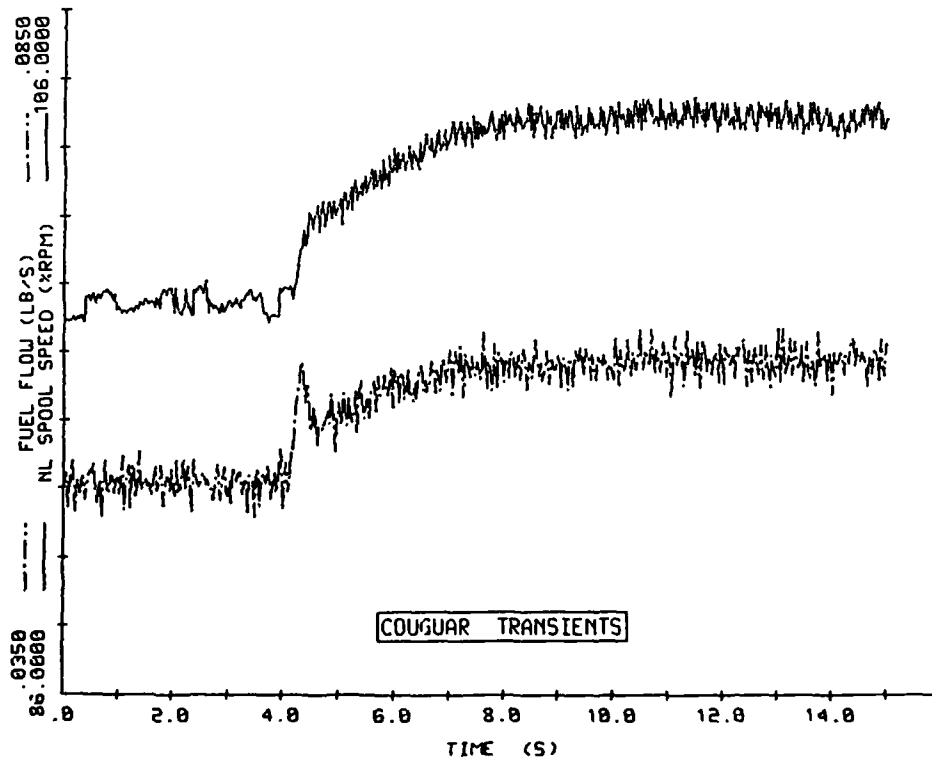


FIG. 4 SMALL ACCELERATION : CLOSED LOOP COUGUAR DATA

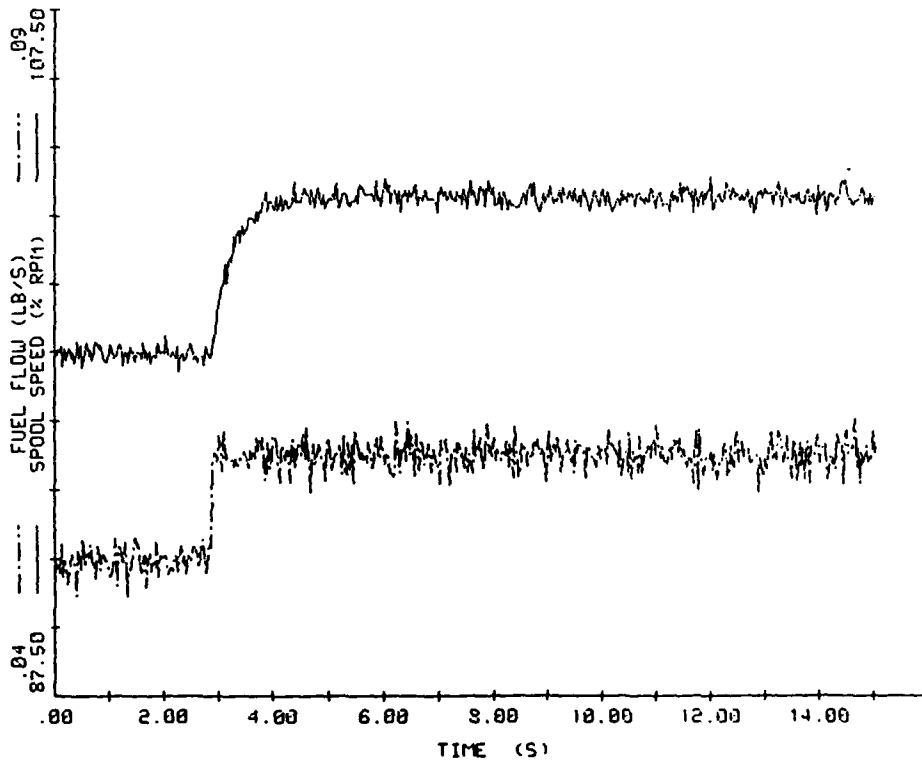


FIG. 5 SIMULATED DATA : FUEL STEP ACCELERATION WITH SUPERIMPOSED WHITE MEASUREMENT NOISE

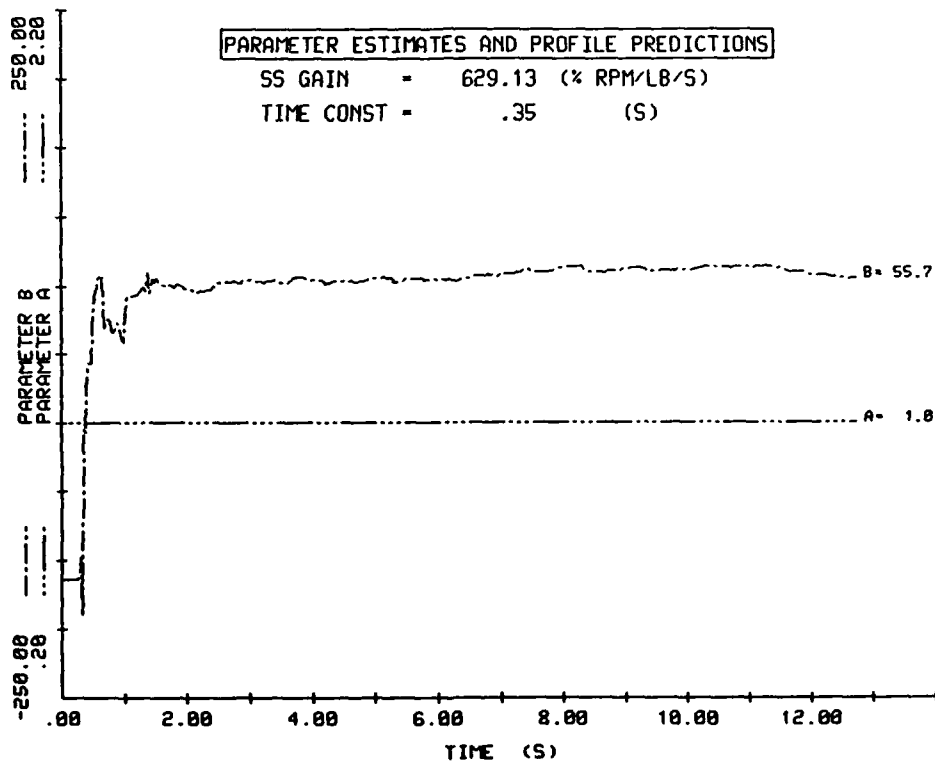


FIG. 6 (a) LSE PREDICTIONS OF THE SPOOL DYNAMICS IN THE PRESENCE OF MODERATE LEVELS OF MEASUREMENT NOISE

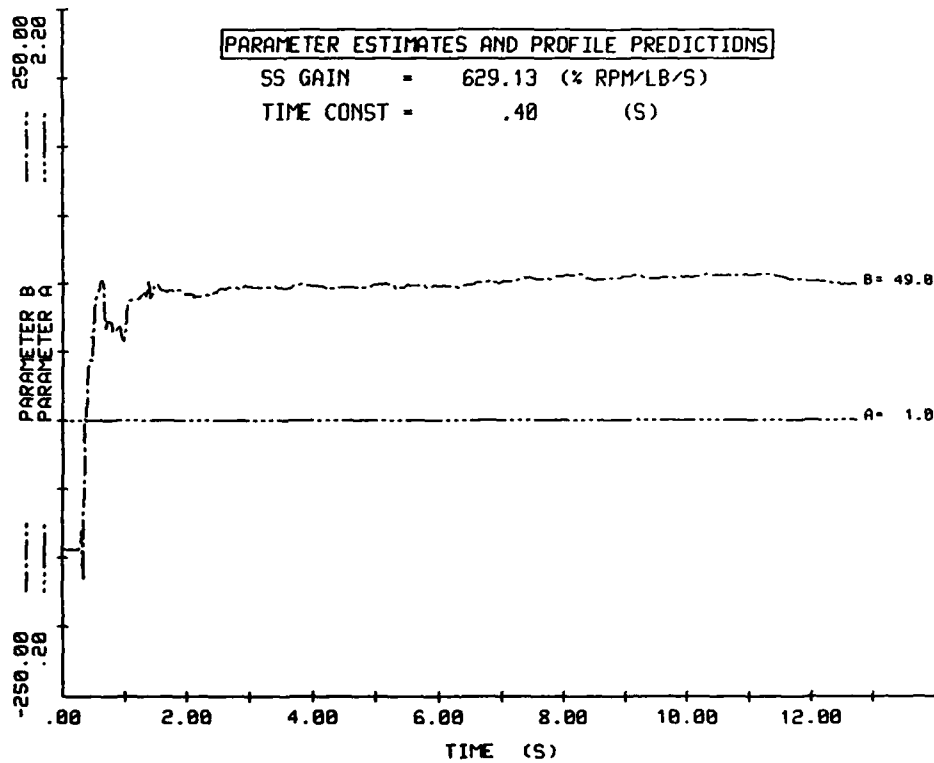


FIG. 6(b) MLSE PREDICTIONS OF THE SPOOL DYNAMICS IN THE PRESENCE OF MODERATE LEVELS OF MEASUREMENT NOISE

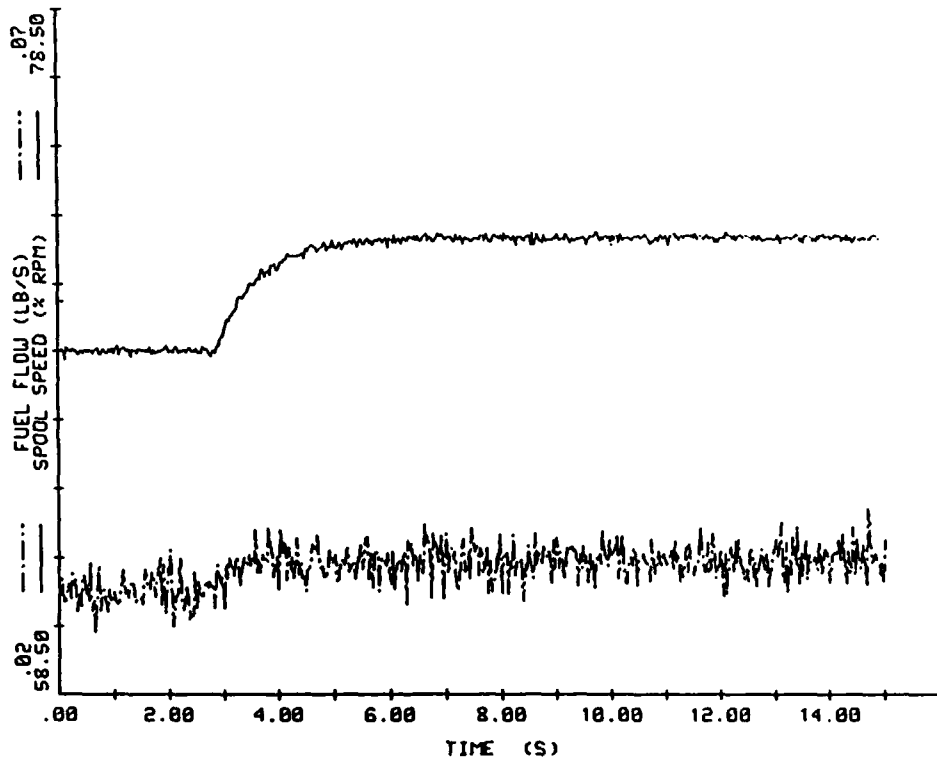


FIG. 7 SIMULATED DATA : FUEL STEP ACCELERATION WITH HIGH LEVELS OF MEASUREMENT NOISE

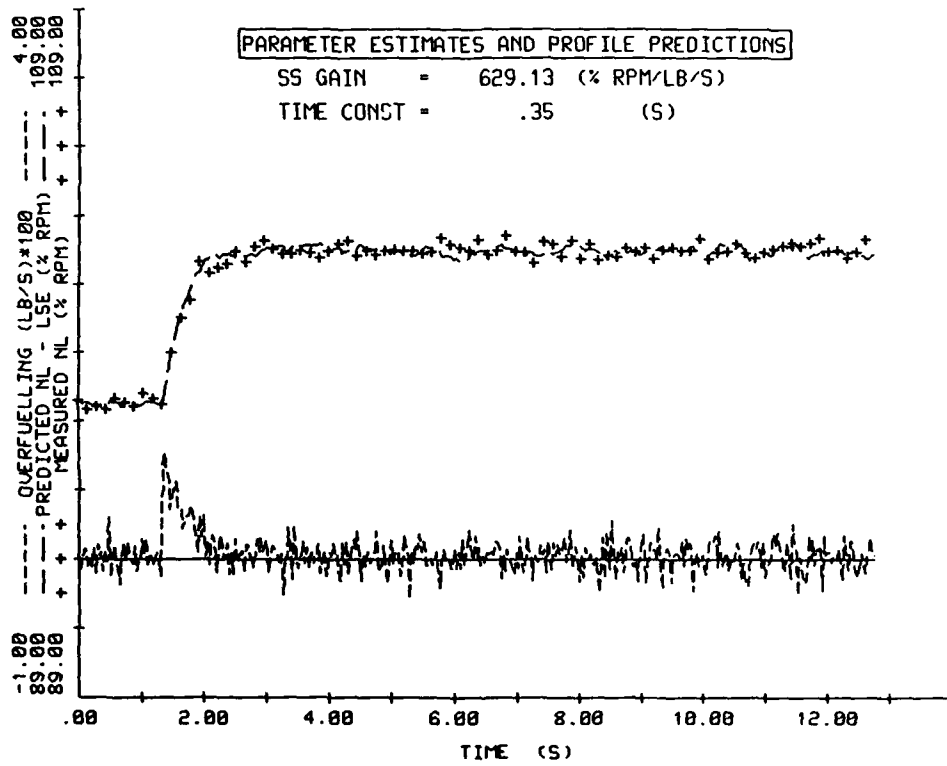


FIG. 8(a) SIMULATED SPOOL SPEED CORRELATIONS IN THE PRESENCE OF MODERATE LEVELS OF MEASUREMENT NOISE - LSE

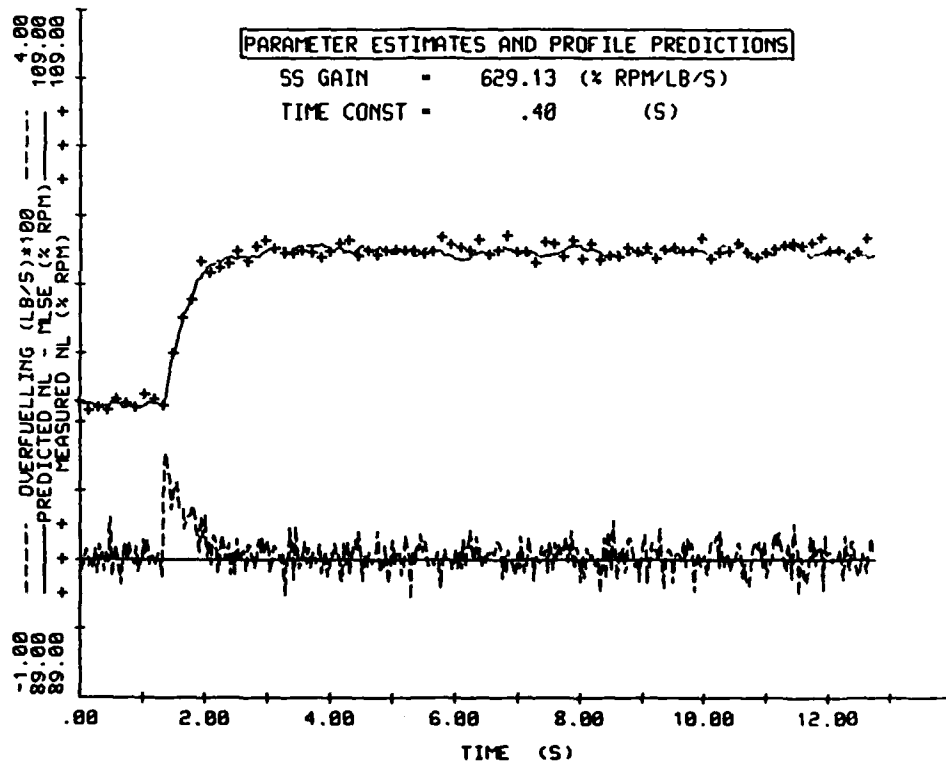


FIG. 8(b) SIMULATED SPOOL SPEED CORRELATIONS IN THE PRESENCE OF MODERATE LEVELS OF MEASUREMENT NOISE: - MLSE

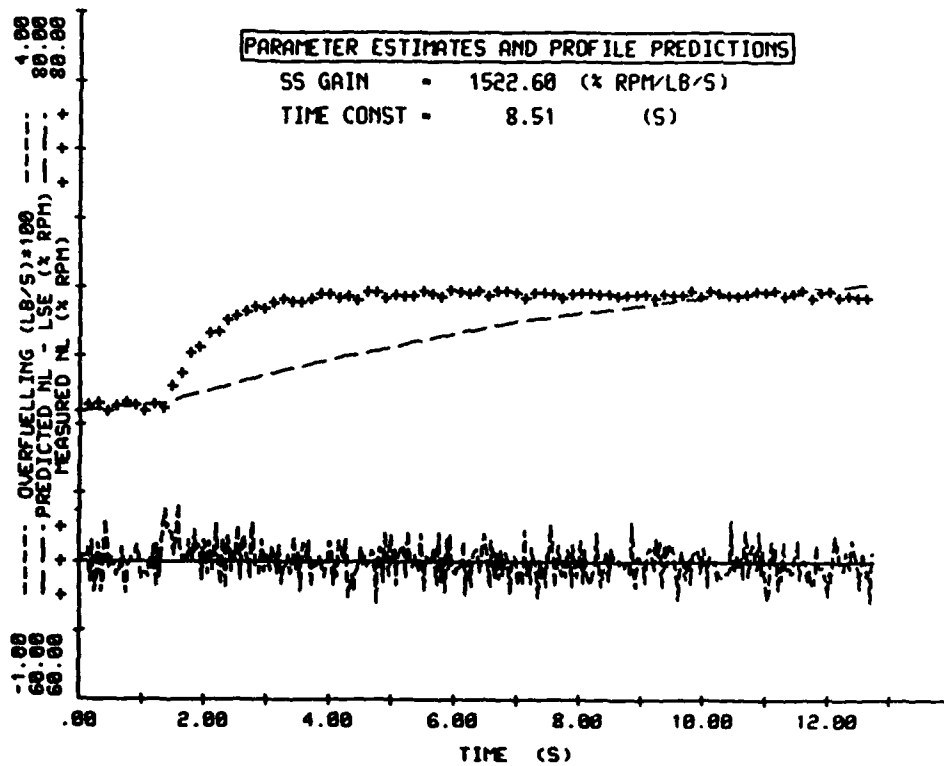


FIG. 9(a) SIMULATED SPOOL SPEED CORRELATIONS IN THE PRESENCE OF HIGH LEVELS OF MEASUREMENT NOISE: - LSE

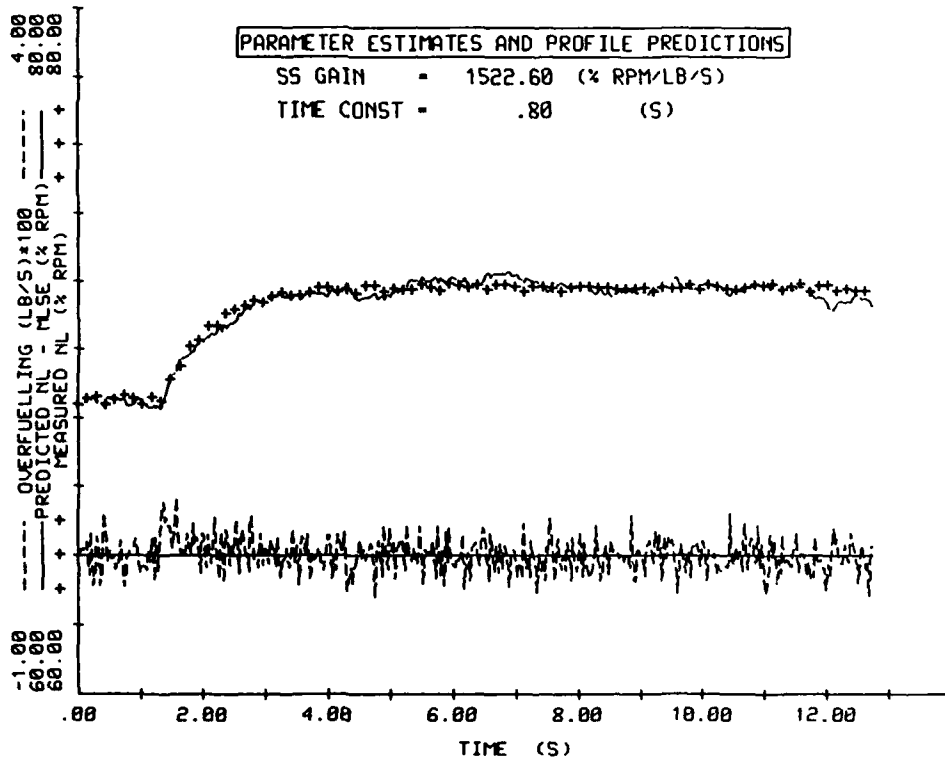


FIG. 9(b) SIMULATED SPOOL SPEED CORRELATIONS IN THE PRESENCE OF HIGH LEVELS OF MEASUREMENT NOISE: - MLSE

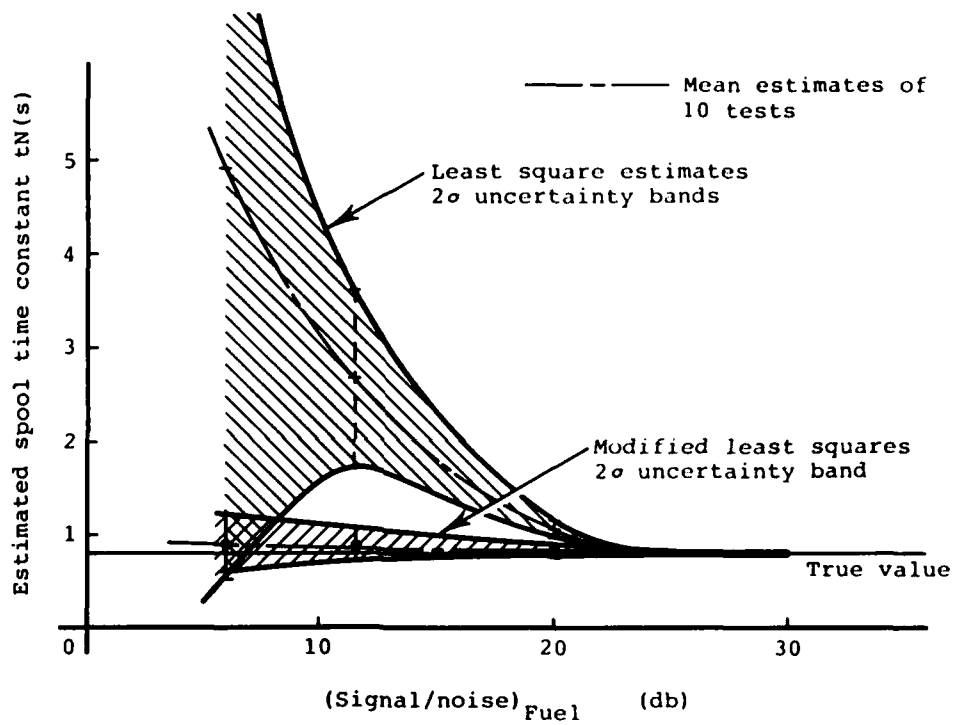


FIG. 10 ESTIMATOR PERFORMANCE WITH VARIOUS LEVELS OF SIGNAL/NOISE RATIO ON THE INPUT SIGNAL: - SPOOL TIME CONSTANT

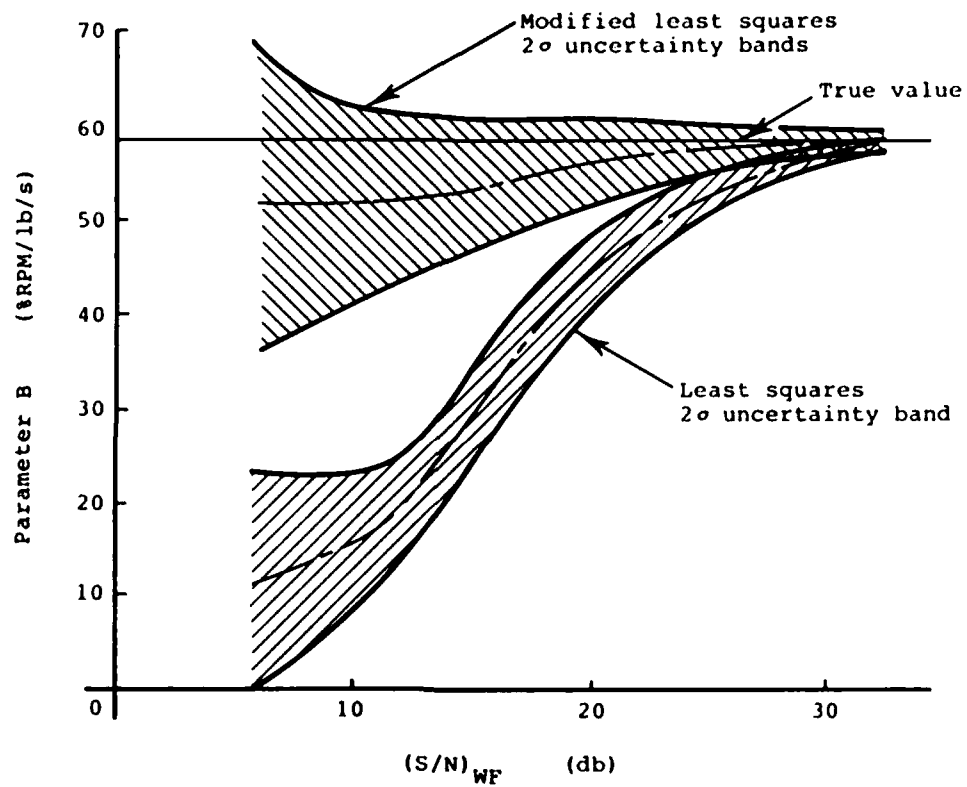


FIG. 11 ESTIMATOR PERFORMANCE WITH VARIOUS LEVELS OF SIGNAL/NOISE RATIO ON THE INPUT SIGNAL: - PARAMETER B IN EQ 3.3

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