FET MODELLING USING THE FETSCG AND FETSCG1 SYSTEMS, PART I: REPORT

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ABSTRACT

This document provides a user-oriented description of the FETSCG and FETSCG1 software systems. These systems implement least one (L_1) and least squares (L_2) optimization techniques in the small-signal, linear circuit modelling of FET devices. The S-parameter sensitivities required for the gradient-based optimization methods are calculated using exact formulas reported by Bandler, Chen and Daijavad.

Both the FETSCG and the FETSCG1 systems have been developed for the IBM/AT personal computers. The mathematical subprograms of these systems and their VAX versions, namely FETSC and FETSC1, are essentially the same. The main difference is that user-interaction has been enhanced for the PC versions by using graphics. The programs are dedicated to two small-signal FET models in current use at Raytheon. Their execution is not encumbered by features, options and circuit descriptions not directly necessary to the particular FET circuit description. FETSCG and FETSCG1 will process up to three sets of measurements at a time, matching corresponding data simultaneously to up to three model circuits by optimizing the parameters of the circuits.

All versions use the familiar SUPERCOMPACT form of user-interaction. Data files and corresponding equivalent circuit parameter files can be created, read, edited and/or saved by appropriate user-interaction.

Two versions are presented herein:

(1) a PC version modelling 11 parameters called FETSCG

(2) a PC version modelling 13 parameters called FETSCG1

FETSCG and FETSCG1 each deal with slightly different equivalent circuit models. These differences are explained and the corresponding differences in coding are highlighted. The structure of the software is described to facilitate changes in the software to enable it to deal with other desired models. Graphics can now be directed to the HP7475 plotter.

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INTRODUCTION

This document reports on the development of a special purpose software system for equivalent circuit representation of FETs by optimization using S-parameters. The software assumes a fixed circuit topology with specific parameter types, and good starting parameter values of the model from previous results or prior low frequency approximations. Versions of the software will run on an IBM/AT. Data files and corresponding equivalent circuit parameter files can be created, read, edited and/or saved by appropriate user-interaction.

The programs presented are dedicated to two small-signal FET models in current use at Raytheon. They incorporate state-of-the-art features such as adjoint sensitivity calculations and efficient gradient optimization. Their execution is not encumbered by features, options and circuit descriptions not directly necessary to the particular FET circuit description. This current set of versions, named FETSCG and FETSCG1, will process up to three sets of measurements at a time, matching corresponding data simultaneously to up to three model circuits by optimizing the parameters of the circuits.

A user-oriented description of the FETSCG and FETSCG1 software systems are provided. They implement least one (L_1) and least squares (L_2) optimization techniques in the modelling process. The S-parameter sensitivities required for the gradient-based optimization methods are calculated using exact formulas by Bandler, Chen and Daijavad[1]. Details of the L_1 optimization algorithm are discussed by Bandler, Kellermann and Madsen[2].

The present document reports on a revision of previous software described in a previous report[3]. Here, FETSCG and FETSCG1 each deal with slightly different equivalent circuit models. These differences are explained and the corresponding differences in coding are highlighted. The structure of the software is described to facilitate changes in the software to enable it to deal with other desired models. Graphics can now be directed to the HP7475 plotter.

The FETSCG and FETSCG1 systems have been developed mainly in Fortran 77 for the IBM/AT with the PC-DOS V3.10 operating system. The mathematical subprograms of these systems and their VAX versions, namely FETSC and FETSC1[4], are essentially the same. The main difference is that user-interaction has been enhanced for the PC versions by using graphics. All versions use the familiar SUPERCOMPACT[5] form of user-interaction.

<u>References</u>

[1] J.W. Bandler, S.H. Chen and S. Daijavad, "Microwave device modelling using efficient L_1 optimization: a novel approach", <u>IEEE Trans. Microwave Theory Tech.</u>, vol.MTT-34, 1986, pp.1282-1293.

[2] J.W. Bandler, W. Kellermann and K. Madsen, "A superlinearly convergent algorithm for nonlinear L_1 optimization with circuit applications", <u>Proc. IEEE Int. Symp. Circuits and Systems</u> (Kyoto, Japan, 1985), pp. 977-980.

[3] "FET modelling using the FETSC system: a user's guide," Report OSA-86-FC-7-R, October 14, 1986.

[4] "FET modelling using the FETSC and FETSC1 system, Part I: Report," Report OSA-87-FC-3-R, February 23, 1987.

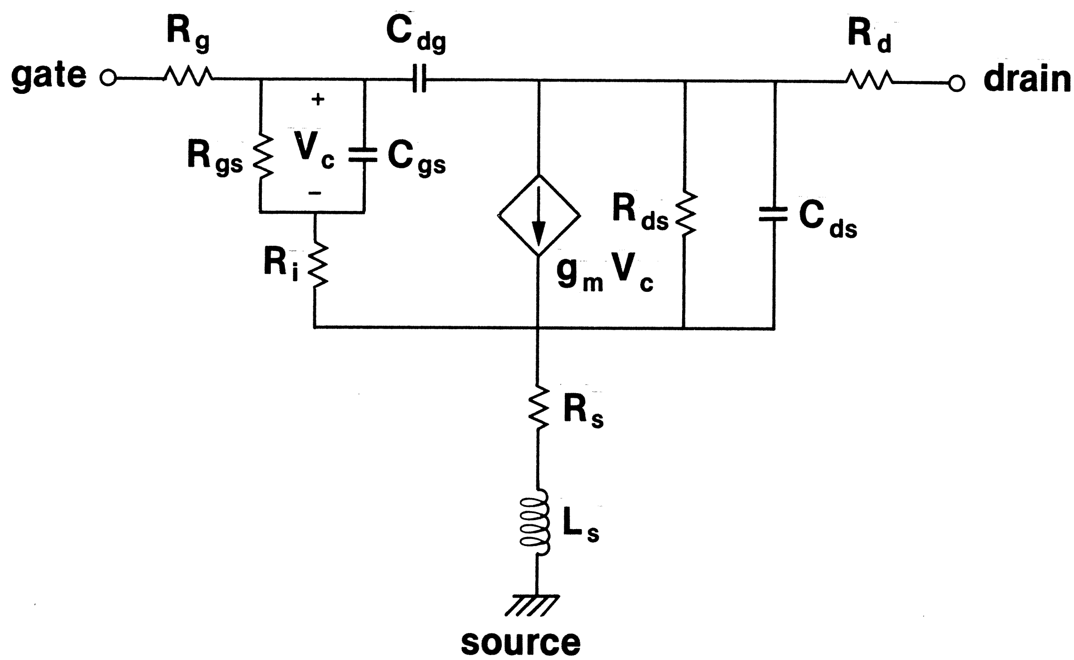
[5] SUPERCOMPACT User Manual, Version 1.6/1.7, July 1982, Revised 1-10-83, updated 3/1/84.

FORMULATION OF THE PROBLEM

The modelling of an FET device is formulated as an optimization problem w.r.t. the equivalent circuit parameters of a fixed proposed topology. The objective is to achieve the best possible match between measured two-port S-parameters and the corresponding calculated S-parameters of the equivalent circuit.

The Equivalent Circuits

The two proposed equivalent circuits are shown in Figs. 1 and 2. For the model illustrated in Fig. 1, there is a total of 11

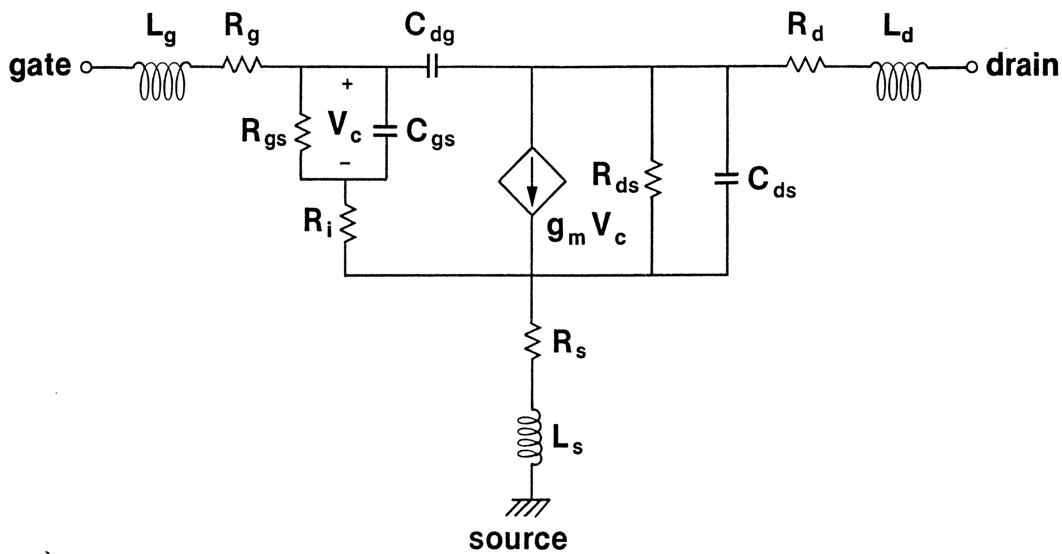


$$y_m = \frac{g_m * e^{-j2\pi f\tau}}{1 + j(f/f_{3dB})}$$

$$f_{3dB} = 1000 \text{ GHz}$$

Fig. 1 Equivalent circuit A of the FET.

parameters which completely define the equivalent circuit at a given frequency f. These parameters are $R_g(\Omega)$, $R_i(\Omega)$, $R_d(\Omega)$, $R_{ds}(\Omega)$, $C_{dg}(pF)$, $C_{gs}(pF)$, $C_{ds}(pF)$, $R_s(\Omega)$, $L_s(nH)$, $g_m(mS)$ and $\tau(ps)$, where the unit for each parameter is given in brackets. For the model illustrated in Fig. 2, there is a total of 13 parameters, namely, $R_g(\Omega)$, $R_i(\Omega)$, $R_d(\Omega)$, $R_{ds}(\Omega)$, $C_{dg}(pF)$, $C_{gs}(pF)$, $C_{ds}(pF)$, $R_s(\Omega)$, $L_s(nH)$, $g_m(mS)$, $\tau(ps)$, $L_g(nH)$ and $L_d(nH)$.



$$y_m = \frac{g_m * e^{-j2\pi f\tau}}{1 + j(f/f_{3dB})}$$

$$f_{3dB} = 1000 \text{ GHz}$$

Fig. 2 Equivalent circuit B of the FET.

Any or all of these parameters could be optimization variables with possible upper and/or lower bounds on their values.

Variable Transformation

An exponential transformation is applied to all variables as follows:

$$x_t = EXP(X_t) + LB_t, \quad t=1,...,n \tag{1}$$

where LB_t is the lower bound on variable x_t. If not explicitly defined by the user, $LB_t = 0$ will be assumed. Such a transformation stablizes the optimization process and automatically ensures that the variables stay within their lower bounds.

<u>The L_1 Optimization</u>

Assume that measurements on all 4 complex S-parameters are available at n_f frequencies, i.e., magnitude and phase of S_{11}, S_{12}, S_{21} and S_{22} for n_f frequencies have been measured. Therefore, we have $S^m_{ij}(k)$, $i = 1,2$, $j = 1,2$, $k = 1,2,\ldots, n_f$, where S_{ij} is the complex S-parameter and m is used to denote the measured response. Similarly, we have $S^c_{ij}(k)$, where c is used to denote the calculated response using the equivalent circuit parameters. $S^c_{ij}(k)$ is a function of circuit parameters, and as mentioned before, we seek optimum circuit parameters such that $S^c_{ij}(k)$ best approximates $S^m_{ij}(k)$.

We define the unweighted error functions as

$$FR_{ij}(k) = \mathrm{Re}[S^m_{ij}(k)] - \mathrm{Re}[S^c_{ij}(k)], \tag{2}$$

$$FI_{ij}(k) = \mathrm{Im}[S^m_{ij}(k)] - \mathrm{Im}[S^c_{ij}(k)], \tag{3}$$

where $i = 1,2$, $j = 1,2$, $k = 1,2,\ldots, n_f$. Given a weighting factor W_{ij}, $i = 1,2$, $j = 1,2$ for an S-parameter S_{ij} (these 4 weighting factors are defined by the user), the normalized weighting factors are calculated as

$$NWR_{ij} = W_{ij}/(\max_k\{\mathrm{Re}[S^m_{ij}(k)]\} - \min_k\{\mathrm{Re}[S^m_{ij}(k)]\}) \tag{4}$$

and

$$NWI_{ij} = W_{ij}/(\max_{k}\{Im[S^{m}_{ij}(k)]\} - \min_{k}\{Im[S^{m}_{ij}(k)]\}). \quad (5)$$

The L_1 objective function is defined as

$$U_1 = \frac{1}{n_f} \sum_{k=1}^{n_f} \sum_{i=1}^{2} \sum_{j=1}^{2} (|NWR_{ij} * FR_{ij}(k)| + |NWI_{ij} * FI_{ij}(k)|). \quad (6)$$

Explicit bounds on variables (if desired) are handled by the L_1 optimization package internally and do not affect the objective function.

The L_2 Optimization

If there are no bounds on variables, the L_2 objective function is given by

$$U_2 = \frac{1}{n_f} \sum_{k=1}^{n_f} \sum_{i=1}^{2} \sum_{j=1}^{2} [(NWR_{ij} * FR_{ij}(k))^2 + (NWI_{ij} * FT_{ij}(k))^2]. \quad (7)$$

The lower bounds on variables are automatically enforced by the variable transformation. The upper bounds on variables are handled by adding a penalty function to the objective function for those variables which violate their bounds. In this case, the objective function is given by

$$PU_2 = U_2 + \sum_{t=1}^{n} [WU_t(UB_t - x_t)^2] \quad (8)$$

where

$$WU_t = \begin{cases} 10, & \text{if } x_t > UB_t, \\ 0, & \text{if } x_t \leq UB_t \end{cases} \quad (9)$$

Actually, in (8) and (9) transformed variable X_t and the transformed value of the bound are used.

SUPERCOMPACT FILE COMPATIBILITY

In this section, a description of circuit and data files which may be utilized with the FETSCG and FETSCG1 systems is given. The user should supply a circuit file which contains directives for a modelling process and, depending on the number of circuits to be processed, one or two or three data files containing the measured S-parameters. The reader is referred to the SUPERCOMPACT user's manual[1] for further guidelines.

Blocks

The following blocks provide information relevant both to FETSCG and FETSCG1 and must be defined in the circuit file:

BLK defines the variables and describes the FET models;

FREQ defines the frequency points;

OPT defines the optimization goals;

DATA specifies the measurement data files;

OUT directs the graphics output. This block is optional.

The blocks LAD and NOI are not allowed since they are irrelevant.

Comments

Comments placed in a circuit file must be preceded by the special symbol '*'. For S-parameter datafiles, a comment line does not have to begin with a '*'. Any line of a datafile that does not begin with a numeral is considered as a comment line.

The BLK Block

1. Defining labels (symbolic names)

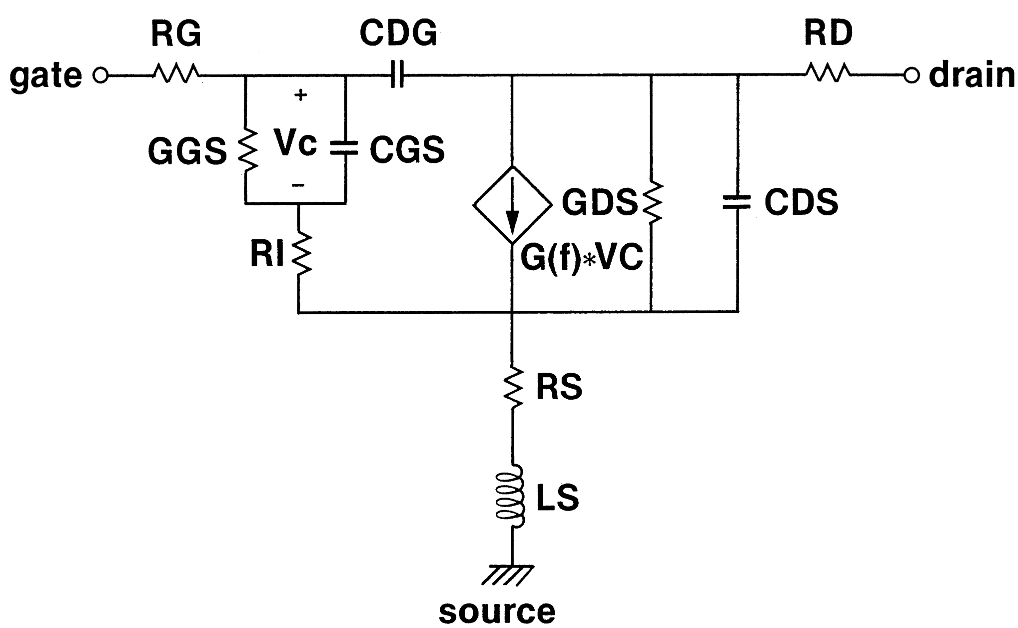
Label_name: V_string

Label_name can have 1 - 8 characters. There must not be any spaces separating the label_name and the symbol ':'. V_string is illustrated by the following examples.

VAR1: 1.2345	a constant
C2: 12.3PF	a constant with a unit
X5: ?5.1?	a variable
L3: ?1NH 10NH 100NH?	a variable with two bounds
X4: ?10% 10NH 1000%?	a variable with percentage bounds

2. Defining a FET

The FET equivalent circuit A shown in Fig. 1 is the only element type permitted in a FETSCG file because it is the only device

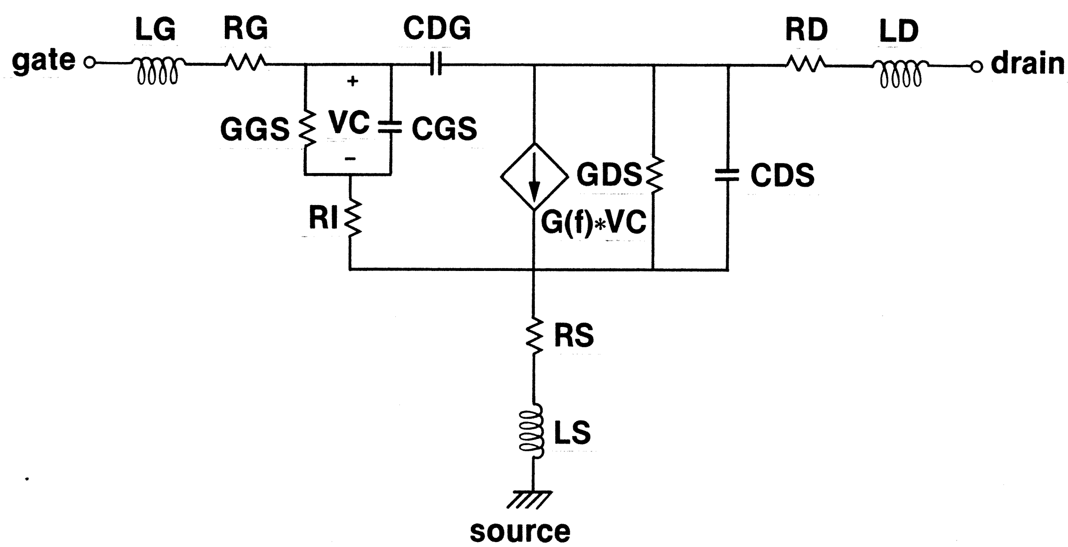


$$G(f) = \frac{G * e^{-j2\pi fT}}{1 + j(f/F)}$$

F = 1000 GHz

Fig. 1 Equivalent circuit A of the FET.

meaningful to the program. The FET element permitted in a FETSCG1 file is shown in Fig. 2.



$$G(f) = \frac{G \ * \ e^{-j2\pi fT}}{1 + j(f/F)}$$

F = 1000 GHz

Fig. 2 Equivalent circuit B of the FET.

Defining any other elements such as RES, CAP, etc., will result in an error. The general form for FETSCG is the following.

```
FET n1 n2 [0] G=x1 CGS=x2 F=x3 T=x4 GGS=x5 CDG=x6 CDS=x7 GDS=x8
+ RI=x9 RG=x10 RD=x11 RS=x12 LS=x13
```

The general form for FETSCG1 is very similar:

```
FET n1 n2 [0] G=x1 CGS=x2 F=x3 T=x4 GGS=x5 CDG=x6 CDS=x7 GDS=x8
+ RI=x9 RG=x10 RD=x11 RS=x12 LG=x13 LD=x14 LS=x15
```

The n1 and n2 are node numbers. The ground node 0 is optional. The x1 to x15 are pre-defined labels or V_strings (see subsection 1 above). F is the 3 dB frequency. Neither it nor GGS can be a variable. If a component is omitted then it is assumed to be zero.

3. Defining a Two-Port

The circuit model should be defined as a two-port whose scattering parameters are to match the measurement data. Consider the following example.

```
Model_name: 2POR n1 n2 [0]
```

Model_name is an arbitrary name having 1 - 8 characters and followed immediately by ':'. The n1 and n2 are node numbers consistent with those of FET. The ground node 0 is optional.

The FREQ Block

The following is an example of the FREQ block.

```
FREQ   1GHZ 2GHZ  STEP 4GHZ 10GHZ 2GHZ
       STEP 14GHZ 17GHZ 1GHZ    20GHZ
```

The meaning of the statement is that 1GHZ, 2GHZ and 20GHZ are discrete points. Two ranges, one from 4GHZ to 10GHZ with an increment of 2GHZ and another from 14GHZ to 17GHZ with an increment of 1GHZ, are also defined. This results in a total of the 11 points:

1, 2, 4, 6, 8, 10, 14, 15, 16, 17 and 20 (GHZ).

Restriction: the total number of frequencies must not exceed 20.

The OPT Block

The format of the OPT block is the following.

```
Model_name [frequency range] S=Measure_name [W w11 w12 w21 w22]
```

'Model_name' must have been defined in the BLK block.

'Frequency range' is optional. If it is omitted then all the frequencies defined in the FREQ block will be used. It could be a single number which specifies a single frequency or it could have two entries specifying a range. In either case, the frequencies specified must be a subset of those defined in the FREQ block.

'S=' means to match scattering parameters. This is the only operation allowed by FETSCG or FETSCG1.

'Measure_name' is to be defined in the DATA block.

'W w11 w12 w21 w22' are optional entries defining weights. The default is unity weighting. The user is warned that the order of the S-parameters is different from that of a data file (which is S11 S21 S12 S22).

The following is an example of the OPT block.

```
OPT
     MODEL1  S=MEASURE1
     MODEL2  3GHZ S=MEASURE2  W 1 0 0 0
             4GHZ 10GHZ S=MEASURE2  W 1 1 1 1
END
```

The DATA Block

The measurement data (scattering parameters of the device) must be supplied through data files. The general form of specifying the name of a data file is

```
Measure_name: file_name
```

The following is an example.

```
DATA

     MEASURE1: C85029A.DAT

     MEASURE2: C85029B.DAT

END
```

The OUT Block

This block is meaningful to FETSCG and FETSCG1 only for the case of multiple-measurement modelling. One of the model-measurement pairs is selected for graphics display during optimization (all the circuits are displayed in sweeping/plotting). The following are examples.

```
OUT

     PLO  MODEL1               * display MODEL1

END

OUT

     PRI MODEL1

     PRI PLO MODEL2            * display MODEL2

END
```

If the OUT block is not defined or no directive 'PLO' is included then the first model will be selected.

Reference

[1] SUPERCOMPACT User Manual, Version 1.6/1.7, July 1982, Revised 1-10-83, updated 3/1/84.

ILLUSTRATED OPERATION OF FETSCG AND FETSCG1

The operation of the FETSCG package on an IBM/AT personal computer is demonstrated with the help of two examples. The first involves a single circuit and the other involves three circuits. The operation of FETSCG1 is identical in all aspects except for the circuit model.

Preparations

You must have an IBM/AT operating under PC-DOS V3.10, having at least 512K RAM, an EGA adaptor and an 8087 coprocessor.

You must have on the diskette the executable file FETSCG.EXE as well as the auxiliary files: the message file FETSCG.MSG and the screen editor CED.EXE.

Single Circuit Example

In this example we seek equivalent circuit parameters for the FET device C85029 under the biasing conditions

VDS=4V, VGS=0V and IDS=177mA.

The S-parameter measurement data file is called C85029A.DAT. In the following interactive session, we employ both L1 and L2 optimizations to identify the parameters and at the same time demonstrate the use of other available commands.

Starting Operation

Assuming that we are operating from drive C (the hard disk), the system prompt should be

```
C>
```

Start the execution of the program by typing, after the system prompt,

```
C>FETSCG
```

Following a menu of commands available, we are at the command level of the FETSCG package.

Creating a Circuit File, READ and TYPE

Using the screen editor, we create a SUPERCOMPACT compatible circuit file called ONECKT.DAT. After creating this file, we are back at the command level of FETSCG and we can use the TYPE command to inspect the contents of the file. As shown in the interactive session, the file has the format of a SUPERCOMPACT circuit file. The SUPERCOMPACT User's Manual[1] should be consulted to recall the function of each block in the circuit file. Next, we read (the READ command) the newly created file (extension DAT is assumed if no other extension is specified). If the circuit file is not SUPERCOMPACT compatible or if some of the other limitations of the package are violated by the circuit file error messages indicating the location and type of error are displayed after reading the file. For example, a limitation is that the package can handle only a prespecified topology for the equivalent circuit and not an arbitrary SUPERCOMPACT circuit file. In that case, the user must use the editor to correct the circuit file before proceeding to other operations. After a successful READ, a few lines display the status of the system in terms of the current files (the circuit file and the measurement data file(s) specified) and the number of circuits.

SWEEP, SENSITIVITY, PARAMETER, %ERROR AND PLOT

Next, the SWEEP command is used to evaluate the S-parameters of the model at the current values of the circuit parameters. The SENSITIVITY command displays the gradient of the least-squares objective w.r.t. the circuit parameters. The PARAMETER command summarizes the current values of parameters and %ERROR displays the percentage error between measured and modelled S-parameters. The PLOT command is used to display, by means of graphics, the match between the model responses and the measured data.

L1 Optimization

Next, we perform the L1 optimization (the L1 command). The objective function is displayed as the optimization proceeds and the optimum parameters are displayed upon the completion of the optimization.

SAVE and COMPARE

At this time we save the optimum parameters in a file called ONECKTL1 (extension DAT) which is the same as ONECKT with the difference that the variables have been updated to their optimum values. The COMPARE command is used to show starting and final values of the circuit parameters side by side. Next in our interactive session, we use the %ERROR command to prove the success of the optimization. A sensitivity analysis is also performed at the solution. Since the sensitivities are evaluated w.r.t. the L2 objective function, displaying the sensitivities after an L2 optimization may be more appropriate. Even after an L1 optimization, however, these sensitivities can be informative.

The BRIEFING Command

Next, the BRIEFING command is used to confirm the names of the current files.

L2 Opimization

To perform the L2 optimization from the same starting values as the ones used for L1, we read ONECKT (.DAT) (using the READ command) and perform the optimization. At the solution, sensitivity analysis is performed and once more the percentage differences between measured and modelled responses are displayed.

FET MODELLING

Interactive Command System

Commands	Available
L1	start modelling using L1 optimization
L2	start modelling using least-squares optimization
STOP	stop this program and return to DOS
DIR	list the file directory
HELP	display the available commands
PARAMETER	display the current model parameters
COMPARE	compare starting point with optimization solution
%ERROR	display percentage errors in S-parameter matching
SWEEP	generate S-parameters of the current model
PLOT	plot the match between model and measurement
SENSITIVITY	sensitivity analysis for the current model
SAVE fname	save current data in a CKT file
READ fname	read desired data from a file
EDIT fn.ext	edit a disk file using full sreen editor
TYPE fn.ext	display the content of a disk file
PRESENTATION	call the user-defined routine PRESENT
BRIEFING	display the current status

```
COMD>ED ONECKT.DAT

          (here, use the screen editor to create a circuit file)

COMD>TYPE ONECKT.DAT

*Single measurement C85029A
BLK
*
        G1:?0.09?
        T1:?0.007NS?
        R1:?1?
        R2:?1?
        R3:?1?
        R4:?1?
        L1:?0.02NH?
        C1:?1.4PF?
        C2:?0.07PF?
        C3:?0.4PF?
        G2:?0.007?
        R0:2.E-6
        F0:1.E3GHZ

*
FET 1 2 G=G1 CGS=C1 F=F0 T=T1 GGS=R0 CDG=C2 CDS=C3 GDS=G2 RI=R1
+  RG=R2 RD=R3 RS=R4 LS=L1
FETMDL1: 2POR 1 2
END
*
FREQ
        STEP 2.0GHZ 18.0GHZ 1.0GHZ
END
*
OPT
FETMDL1  F=2.0GHZ 18.0GHZ  S=FETMDA1 W 1 1 1 1
END
*
DATA
FETMDA1: C85029A.DAT
END


COMD>READ ONECKT
    Reading file: ONECKT.DAT

    Working file: ONECKT.DAT
    Number of circuits:  1
    Measurement files: C85029A.DAT
```

COMD>SW

* S-PARAMETERS OF MODEL FETMDL1

* Frequency (GHZ)	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	0.9102	-90.02	4.1038	116.16	0.0489	41.02	0.4654	-47.70
3.0	0.8804	-112.39	3.1186	97.38	0.0548	29.87	0.4655	-62.14
4.0	0.8662	-126.48	2.4464	83.11	0.0559	23.49	0.4852	-73.54
5.0	0.8603	-135.94	1.9780	71.44	0.0550	20.06	0.5148	-83.03
6.0	0.8588	-142.69	1.6380	61.43	0.0530	18.75	0.5485	-91.16
7.0	0.8595	-147.76	1.3817	52.60	0.0505	19.18	0.5830	-98.24
8.0	0.8614	-151.73	1.1823	44.69	0.0481	21.15	0.6162	-104.47
9.0	0.8640	-154.94	1.0231	37.52	0.0460	24.52	0.6474	-110.00
10.0	0.8668	-157.62	0.8935	31.00	0.0445	29.07	0.6760	-114.97
11.0	0.8696	-159.91	0.7859	25.05	0.0438	34.49	0.7020	-119.43
12.0	0.8723	-161.90	0.6954	19.62	0.0440	40.37	0.7253	-123.48
13.0	0.8748	-163.65	0.6183	14.65	0.0451	46.27	0.7462	-127.16
14.0	0.8772	-165.23	0.5518	10.12	0.0471	51.81	0.7647	-130.53
15.0	0.8792	-166.65	0.4938	6.00	0.0498	56.75	0.7812	-133.62
16.0	0.8811	-167.94	0.4429	2.26	0.0531	61.00	0.7958	-136.46
17.0	0.8827	-169.14	0.3978	-1.12	0.0569	64.56	0.8087	-139.09
18.0	0.8840	-170.24	0.3576	-4.13	0.0611	67.49	0.8202	-141.52

COMD>SE

SENSITIVITY OF THE CURRENT MODEL

least-squares error: 1.43289185

FETMDL1 gradient	
0.006588	RG (OH)
-0.002924	RD (OH)
-0.054016	GDS(/OH)
0.008720	RI (OH)
-0.029135	RS (OH)
0.083693	LS (nH)
0.785485	CGS (pF)
0.178493	CDG (pF)
0.846271	CDS (pF)
-0.219883	G (/OH)
0.173734	T (ps)

COMD>PA

FET MODEL PARAMETERS file: ONECKT.DAT

FETMDL1	
1.00000	RG (OH)
1.00000	RD (OH)
.00700	GDS(/OH)
1.00000	RI (OH)
1.00000	RS (OH)
.02000	LS (nH)
1.40000	CGS (pF)
.07000	CDG (pF)
.40000	CDS (pF)
.09000	G (/OH)
7.00000	T (ps)

COMD>%ER

PERCENTAGE ERRORS IN S-PARAMETER MATCHING
ABS[(Model-Measurement)/Measurement] %
model: FETMDL1 measurement: C85029A.DAT

Frequency (GHZ)	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	4.65%	92.68%	1.57%	20.19%	68.04%	34.84%	22.56%	122.59%
3.0	6.27%	67.79%	13.73%	24.67%	41.15%	43.07%	19.86%	89.34%
4.0	3.15%	51.95%	26.58%	29.86%	22.16%	44.83%	15.15%	84.17%
5.0	2.11%	38.79%	33.04%	30.54%	8.42%	40.83%	9.69%	69.67%
6.0	0.12%	31.06%	38.02%	35.52%	2.24%	34.80%	5.55%	66.29%
7.0	1.60%	22.15%	39.78%	36.51%	2.26%	4.02%	2.58%	54.90%
8.0	2.70%	18.74%	43.67%	43.39%	4.35%	11.40%	5.43%	52.42%
9.0	3.60%	12.56%	46.78%	44.40%	8.87%	90.96%	10.34%	45.55%
10.0	3.81%	9.98%	50.32%	47.41%	15.21%	176.60%	11.02%	44.27%
11.0	4.44%	6.96%	50.60%	55.54%	12.23%	178.84%	13.85%	43.53%
12.0	4.77%	4.28%	53.96%	57.80%	13.26%	560.76%	14.04%	34.72%
13.0	6.74%	1.64%	55.32%	64.11%	4.69%	428.18%	16.10%	36.16%
14.0	5.67%	0.58%	57.38%	70.70%	0.97%	999.00%	15.29%	29.11%
15.0	6.68%	3.11%	57.48%	75.84%	12.61%	999.00%	16.28%	25.56%
16.0	5.74%	3.83%	60.92%	90.59%	21.82%	739.07%	16.26%	25.57%
17.0	7.77%	6.01%	57.52%	109.40%	39.56%	999.00%	14.80%	22.28%
18.0	5.32%	5.76%	63.09%	150.88%	45.57%	999.00%	15.55%	22.83%

COMD>PLOT

(see next section GRAPHICS GENERATED BY FETSCG and FETSCG1)

COMD>L1

(see next section GRAPHICS GENERATED BY FETSCG and FETSCG1)

Optimization Completed
after 13 iterations
FET MODEL PARAMETERS
FETMDL1

starting	solution	
1.00000	3.06509	RG (OH)
1.00000	3.07359	RD (OH)
.00700	.00506	GDS(/OH)
1.00000	.01378	RI (OH)
1.00000	.94576	RS (OH)
.02000	.00490	LS (nH)
1.40000	.67515	CGS (pF)
.07000	.03033	CDG (pF)
.40000	.22060	CDS (pF)
.09000	.06727	G (/OH)
7.00000	4.74320	T (ps)

COMD>SAVE ONECKTL1

```
COMD>COMPARE

          FET MODEL PARAMETERS
            FETMDL1
      starting        solution
       1.00000         3.06509  RG  (OH)
       1.00000         3.07359  RD  (OH)
        .00700          .00506  GDS(/OH)
       1.00000          .01378  RI  (OH)
       1.00000          .94576  RS  (OH)
        .02000          .00490  LS  (nH)
       1.40000          .67515  CGS (pF)
        .07000          .03033  CDG (pF)
        .40000          .22060  CDS (pF)
        .09000          .06727  G  (/OH)
       7.00000         4.74320  T   (ps)

COMD>%ER
```

PERCENTAGE ERRORS IN S-PARAMETER MATCHING

ABS[(Model-Measurement)/Measurement] %

Frequency (GHZ)	model: FETMDL1 MS11	AS11	MS21	AS21	measurement: C85029A.DAT MS12	AS12	MS22	AS22
2.0	0.55%	8.21%	9.47%	2.47%	0.96%	5.34%	0.58%	12.49%
3.0	1.15%	5.15%	7.77%	2.24%	0.27%	8.80%	0.01%	3.80%
4.0	0.78%	3.68%	1.68%	4.44%	2.44%	9.43%	0.38%	6.94%
5.0	0.22%	0.89%	0.30%	0.75%	4.75%	7.82%	0.89%	2.87%
6.0	0.73%	0.13%	2.66%	3.01%	2.90%	11.45%	2.53%	4.43%
7.0	1.14%	3.55%	1.40%	1.24%	0.92%	12.96%	0.56%	0.25%
8.0	1.16%	3.64%	4.51%	3.45%	2.24%	10.01%	0.77%	1.29%
9.0	1.16%	6.70%	7.03%	2.59%	1.23%	9.51%	0.66%	0.97%
10.0	0.66%	7.28%	10.82%	6.55%	3.88%	10.57%	1.06%	0.24%
11.0	0.72%	8.61%	9.04%	0.87%	0.68%	21.76%	0.26%	1.64%
12.0	0.59%	9.91%	13.13%	10.26%	4.37%	33.68%	1.29%	2.96%
13.0	2.13%	11.39%	13.63%	12.73%	0.00%	19.58%	0.32%	0.40%
14.0	0.84%	12.67%	15.57%	18.90%	1.19%	42.57%	1.53%	4.23%
15.0	1.60%	14.36%	13.65%	46.59%	1.26%	46.37%	0.96%	5.68%
16.0	0.56%	14.54%	18.53%	33.18%	0.32%	21.85%	1.09%	4.57%
17.0	2.39%	16.11%	8.95%	133.23%	3.40%	14.63%	2.32%	6.09%
18.0	0.00%	15.55%	18.51%	191.58%	2.51%	2.55%	1.57%	4.76%

```
COMD>SE
        SENSITIVITY OF THE CURRENT MODEL
        least-squares error:     0.07406536
          FETMDL1
          gradient
         -0.006281     RG  (OH)
          0.001076     RD  (OH)
         -0.016698     GDS(/OH)
         -0.000038     RI  (OH)
         -0.005747     RS  (OH)
         -0.002337     LS  (nH)
         -0.075147     CGS (pF)
         -0.007044     CDG (pF)
          0.000188     CDS (pF)
          0.048472     G  (/OH)
         -0.003302     T   (ps)

COMD>BR

    Working file: ONECKTL1.DAT
    Number of circuits: 1
    Measurement files: C85029A.DAT

COMD>READ ONECKT
    Reading file: ONECKT.DAT

    Working file: ONECKT.DAT
    Number of circuits:  1
    Measurement files: C85029A.DAT

COMD>L2

         (see next section GRAPHICS GENERATED BY FETSCG and FETSCG1)

      Optimization Completed
     after   72 iterations
         FET MODEL PARAMETERS
           FETMDL1
      starting       solution
       1.00000        4.95310  RG  (OH)
       1.00000        1.81221  RD  (OH)
        .00700         .00542  GDS(/OH)
       1.00000         .00162  RI  (OH)
       1.00000        1.05732  RS  (OH)
        .02000         .00449  LS  (nH)
       1.40000         .73901  CGS (pF)
        .07000         .03238  CDG (pF)
        .40000         .21629  CDS (pF)
        .09000         .06983  G  (/OH)
       7.00000        3.51917  T   (ps)
```

```
COMD>SE

        SENSITIVITY OF THE CURRENT MODEL
        least-squares error:      .06443907
          FETMDL1
          gradient
           .011208     RG  (OH)
           .001472     RD  (OH)
           .006026     GDS(/OH)
           .000002     RI  (OH)
          -.005945     RS  (OH)
          -.001449     LS  (nH)
           .052769     CGS (pF)
           .019724     CDG (pF)
           .008010     CDS (pF)
          -.031041     G  (/OH)
          -.009989     T   (ps)

COMD>%ER
```

PERCENTAGE ERRORS IN S-PARAMETER MATCHING
ABS[(Model-Measurement)/Measurement] %

Frequency model: FETMDL1 measurement: C85029A.DAT

(GHZ)	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	1.31%	15.85%	8.93%	3.59%	6.50%	8.74%	4.40%	17.28%
3.0	4.22%	11.50%	5.29%	3.45%	3.39%	13.25%	3.96%	7.19%
4.0	3.31%	9.00%	2.13%	5.39%	.22%	14.51%	4.10%	9.68%
5.0	4.53%	5.34%	5.09%	1.26%	3.49%	13.21%	4.13%	5.05%
6.0	4.52%	3.70%	8.06%	2.86%	2.19%	16.45%	5.17%	6.36%
7.0	4.48%	.29%	7.40%	2.22%	.51%	7.28%	1.57%	1.91%
8.0	4.74%	.73%	10.70%	1.60%	2.52%	13.61%	2.33%	2.82%
9.0	4.96%	4.15%	13.31%	5.69%	1.53%	6.79%	.42%	.41%
10.0	5.61%	4.97%	17.03%	11.13%	3.46%	10.10%	1.67%	1.53%
11.0	5.71%	6.51%	15.51%	6.71%	.02%	20.02%	.48%	2.84%
12.0	5.97%	7.99%	19.39%	18.56%	3.43%	40.96%	1.15%	1.90%
13.0	4.66%	9.63%	19.91%	23.54%	1.36%	12.32%	.13%	.61%
14.0	5.98%	11.05%	21.74%	33.23%	.60%	60.44%	.80%	3.34%
15.0	5.38%	12.87%	19.97%	68.65%	3.60%	68.96%	.01%	4.88%
16.0	6.43%	13.14%	24.49%	58.16%	2.53%	8.57%	.08%	3.83%
17.0	4.82%	14.81%	15.57%	187.89%	6.96%	34.08%	.97%	5.43%
18.0	7.13%	14.31%	24.40%	277.67%	1.45%	18.41%	.04%	4.14%

```
COMD>SAVE ONECKTL2

COMD>STOP
```

Multi-Circuit Example

A powerful feature of the FETSCG system is its capability in handling multiple circuits which may have common variables. Up to three circuits can be processed simultaneously. The theoretical advantages of the multi-circuit approach in modelling have been discussed by Bandler, Chen and Daijavad in a recent paper[2]. Here, we use an example to demonstrate the use of FETSCG with multiple circuits.

S-parameter measurements on an FET device under three different biasing conditions have been provided by Raytheon. The biasing conditions and the corresponding data files are as follows.

Biasing Conditions			Measurement Data File
VDS=4V	VGS= 0V	IDS=177mA	C85029A.DAT
VDS=4V	VGS=-1.74V	IDS= 92mA	C85029B.DAT
VDS=4V	VGS=-3.10V	IDS= 37mA	C85029C.DAT

In an interactive session which follows, we simultaneously process the three sets of measurements to find parameters for the corresponding circuits. By using common variables between the circuits, we can easily force the assumption that some parameters should remain unchanged as the biasing conditions vary. In particular, parameters RGM, RD, LS and T are declared to be fixed w.r.t. the bias. The frequencies for the measurements are from 2 to 18GHz, 1GHz apart. We use half the frequency points, i.e., from 2 to 18GHz with a 2GHz increment.

As seen from the following printout of the interactive session, we first create SUPERCOMPACT compatible file ALLTHREE.DAT. The listing of this file (obtained using the TYPE command) illustrates the way that common or noncommon variables between the three circuits are handled. The OPT block in the file specifies that each circuit response models its corresponding measurement file.

Next, we perform the L1 optimization and obtain the parameters of the three circuits. Inspecting the parameters, we observe that the assumptions on common variables have been realized. The percentage difference between modelled and measured responses of each circuit are displayed using the %ERROR command and sensitivities of the least-squares objective are calculated using the SENSITIVITY command.

```
COMD>ED ALLTHREE.DAT


COMD>TYPE ALLTHREE.DAT

*All three measurements C85029A, C85029B and C85029C
BLK
*       common variables
        R0:2.E-6
        F0:1.E3GHZ
        RGM:?1?
        LS:?0.02NH?
        RDD:?1?
        TAU:?0.007NS?
*       variable for the first circuit
        G1:?0.09?
        C1:?1.4PF?
        C2:?0.07PF?
        C3:?0.04PF?
        R1:?1?
        R2:?1?
        GG3:?0.007?
*       variable for the second circuit
        G2:?0.09?
        C4:?1.4PF?
        C5:?0.07PF?
        C6:?0.04PF?
        R4:?1?
        R5:?1?
        GG6:?0.007?
*       variable for the third circuit
        G3:?0.09?
        C7:?1.4PF?
        C8:?0.07PF?
        C9:?0.04PF?
        R7:?1?
        R8:?1?
        GG9:?0.007?
*
FET 1 2 G=G1 CGS=C1 F=F0 T=TAU GGS=R0 CDG=C2 CDS=C3 GDS=GG3 RI=R1 RG=RGM
+   RD=RDD RS=R2 LS=LS
FETMDL1: 2POR 1 2
FET 3 4 G=G2 CGS=C4 F=F0 T=TAU GGS=R0 CDG=C5 CDS=C6 GDS=GG6 RI=R4 RG=RGM
+   RD=RDD RS=R5 LS=LS
FETMDL2: 2POR 3 4
FET 5 6 G=G3 CGS=C7 F=F0 T=TAU GGS=R0 CDG=C8 CDS=C9 GDS=GG9 RI=R7 RG=RGM
+   RD=RDD RS=R8 LS=LS
FETMDL3: 2POR 5 6
END
*
FREQ
        STEP 2.0GHZ 18.0GHZ 2.0GHZ
END
*
```

```
OPT
FETMDL1  F=2.0GHZ 18.0GHZ  S=FETMDA1 W 1 1 1 1
FETMDL2  F=2.0GHZ 18.0GHZ  S=FETMDA2
FETMDL3  F=2.0GHZ 18.0GHZ  S=FETMDA3
END
*
DATA
FETMDA1: C85029A.DAT
FETMDA2: C85029B.DAT
FETMDA3: C85029C.DAT
END

COMD>READ ALLTHREE
    Reading file: ALLTHREE.DAT

    Working file: ALLTHREE.DAT
    Number of circuits: 3
    Measurement files: C85029A.DAT   C85029B.DAT   C85029C.DAT

COMD>PA
          FET MODEL PARAMETERS
    FETMDL1           FETMDL2           FETMDL3
     1.00000           1.00000           1.00000       RG   (OH)
     1.00000           1.00000           1.00000       RD   (OH)
     0.00700           0.00700           0.00700       GDS(/OH)
     1.00000           1.00000           1.00000       RI   (OH)
     1.00000           1.00000           1.00000       RS   (OH)
     0.02000           0.02000           0.02000       LS   (nH)
     1.40000           1.40000           1.40000       CGS  (pF)
     0.07000           0.07000           0.07000       CDG  (pF)
     0.04000           0.04000           0.04000       CDS  (pF)
     0.09000           0.09000           0.09000       G   (/OH)
     7.00000           7.00000           7.00000       T    (ps)
```

COMD>L1

(see next section GRAPHICS GENERATED BY FETSCG and FETSCG1)

Optimization Completed
after 17 iterations
FET MODEL PARAMETERS

FETMDL1		FETMDL2		FETMDL3		
starting	solution	starting	solution	starting	solution	
1.0000	2.2768	1.0000	2.2768	1.0000	2.2768	RG (OH)
1.0000	3.5793	1.0000	3.5793	1.0000	3.5793	RD (OH)
.0070	.0050	.0070	.0059	.0070	.0059	GDS(/OH)
1.0000	.0569	1.0000	.3402	1.0000	.5920	RI (OH)
1.0000	.9679	1.0000	.4929	1.0000	.0376	RS (OH)
.0200	.0046	.0200	.0046	.0200	.0046	LS (nH)
1.4000	.6563	1.4000	.4057	1.4000	.3190	CGS (pF)
.0700	.0296	.0700	.0492	.0700	.0620	CDG (pF)
.0400	.2218	.0400	.2168	.0400	.2072	CDS (pF)
.0900	.0633	.0900	.0497	.0900	.0394	G (/OH)
7.0000	4.2061	7.0000	4.2061	7.0000	4.2061	T (ps)

COMD>%ER

PERCENTAGE ERRORS IN S-PARAMETER MATCHING
ABS[(Model-Measurement)/Measurement] %

Frequency	model: FETMDL1				measurement: C85029A.DAT			
(GHZ)	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	1.32%	5.33%	4.47%	1.61%	.45%	3.80%	1.03%	9.44%
4.0	2.61%	1.66%	1.71%	3.01%	2.48%	6.83%	1.68%	5.19%
6.0	3.15%	1.55%	5.25%	1.12%	2.13%	8.29%	.63%	3.46%
8.0	3.88%	4.68%	6.82%	1.06%	3.52%	6.42%	.78%	.77%
10.0	3.52%	8.08%	12.95%	9.99%	2.40%	15.24%	.02%	.00%
12.0	3.51%	10.54%	15.26%	15.05%	2.67%	39.11%	.66%	3.04%
14.0	3.80%	13.18%	17.72%	26.05%	.79%	46.81%	1.30%	4.20%
16.0	3.52%	14.97%	20.69%	44.67%	1.95%	21.41%	1.24%	4.48%
18.0	2.93%	15.93%	20.73%	229.40%	.00%	.05%	2.03%	4.63%

Press any key to continue ...

PERCENTAGE ERRORS IN S-PARAMETER MATCHING
ABS[(Model-Measurement)/Measurement] %

Frequency	model: FETMDL2				measurement: C85029B.DAT			
(GHZ)	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	.88%	2.30%	8.71%	1.18%	9.18%	4.47%	.01%	16.21%
4.0	.64%	.42%	3.77%	2.46%	6.72%	9.27%	.03%	10.56%
6.0	.09%	3.46%	.20%	.50%	5.01%	14.07%	3.70%	7.21%
8.0	.63%	6.50%	1.52%	.07%	7.16%	19.38%	2.38%	3.18%
10.0	.44%	10.27%	7.25%	9.05%	.52%	16.96%	3.21%	.04%
12.0	1.39%	12.78%	8.74%	13.04%	1.28%	31.38%	1.62%	3.10%
14.0	1.71%	15.38%	11.01%	19.25%	.75%	17.51%	1.70%	5.10%
16.0	3.14%	17.26%	13.61%	26.28%	.01%	.09%	.26%	5.66%
18.0	3.17%	17.97%	14.63%	55.58%	1.39%	9.11%	.68%	4.68%

Press any key to continue ...

PERCENTAGE ERRORS IN S-PARAMETER MATCHING
ABS[(Model-Measurement)/Measurement] %

model: FETMDL3 measurement: C85029C.DAT

Frequency (GHZ)	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	.59%	2.63%	9.50%	1.17%	12.57%	5.08%	.53%	17.94%
4.0	.00%	.00%	4.58%	2.43%	9.31%	10.12%	.41%	11.95%
6.0	1.44%	3.40%	.25%	.49%	6.44%	15.79%	3.84%	8.15%
8.0	.10%	6.59%	.76%	.02%	7.72%	20.89%	2.67%	3.67%
10.0	.04%	10.73%	7.01%	8.91%	.46%	17.49%	3.35%	.05%
12.0	1.51%	13.37%	8.30%	13.37%	1.56%	1.67%	1.16%	3.36%
14.0	2.60%	16.00%	10.71%	18.68%	.94%	15.73%	2.34%	5.44%
16.0	4.05%	18.00%	12.78%	26.23%	1.05%	4.65%	1.33%	6.09%
18.0	5.09%	18.91%	13.12%	56.10%	1.06%	9.78%	.05%	5.08%

COMD>SE

SENSITIVITY OF THE CURRENT MODEL
least-squares error: .10247020

FETMDL1 gradient	FETMDL2 gradient	FETMDL3 gradient	
-.001986	-.003484	-.003604	RG (OH)
.000935	-.000599	-.000779	RD (OH)
.000940	-.007108	-.006840	GDS(/OH)
-.000063	-.000558	-.000906	RI (OH)
-.000650	-.000713	-.000051	RS (OH)
-.000897	-.000928	-.000848	LS (nH)
-.021547	-.053503	-.049446	CGS (pF)
-.001641	-.014390	-.020706	CDG (pF)
-.000305	.001251	.003735	CDS (pF)
-.017855	.017322	.011877	G (/OH)
-.003700	-.001884	-.001764	T (ps)

COMD>STOP

References

[1] SUPERCOMPACT User Manual, Version 1.6/1.7, July 1982, Revised 1-10-83, updated 3/1/84.

[2] J.W. Bandler, S.H. Chen and S. Daijavad, "Microwave device modelling using efficient L_1 optimization: a novel approach", IEEE Trans. Microwave Theory Tech., vol. MTT-34, 1986, pp. 1282-1293.

GRAPHICS GENERATED BY FETSCG AND FETSCG1

In this section graphics generated from the data files as well as results of simultaneous optimization of the three circuit models described in the section on OPERATION are presented.

Figures 1-3 depict curves at the start of optimization. Figures 4-6 depict curves after L_1 optimization. Figures 7-9 depict curves after L_2 optimization.

Command PLOT

Responding to the command PLOT, the program will generate graphics showing the match between the current model and the measured data. A menu line will show up on the top of the screen such as:

```
Model: FETMDL1    File: C85029A.DAT       <CR> or P=plot
```

You may simply press the CR (carriage return or <Enter>) key to exit the current graphics and proceed with other operations, or you may press the 'P' key to generate a hardcopy of the graphics using an HP plotter. If you press 'P', another menu line will appear:

```
Plot defaults: XMARG=3.5cm, YMARG=3.5cm, char=3.5% of box. (y/n)?
```

This means that by default the hardcopy will have a horizontal margin of 3.5cm on both the left and the right sides and a vertical margin of 3.5cm on both the top and the bottom. The size of the characters for labelling will be 3.5% of the size of the box. If you press 'y', these default values are taken. Pressing 'n' indicates that a change is desired. In that case, the following message appears:

```
Enter: XMARG cm, YMARG cm, char (% box) :
```

The numbers that you enter will replace the default values.

The program will give instructions for mounting color pens on the HP plotter:

```
 Prepare plotter pens: P1 box, P2 model, P3 measurement.   <CR> when ready.
```

You can set the color of these pens as you wish.

Setting Up HP7475 Plotter

Before running a program which outputs to the plotter, make sure that the plotter/computer interface is set up properly. In its present state, the subroutine FETPLT specifies device COM1 for the IBM/AT computer.

IBM/AT serial port configuration:

use DOS "MODE" command to configure COM1 device:

```
C> MODE COM1:96,N,8,1,P

where   COM1    specifies the device
96      specifies 9600 baud --------------|---  all these
N       specifies no parity check --------|     as per
8       specifies 8 data bits ------------|     switches on
1       specifies 1 stop bit -------------|     the plotter
P       for continuous retry of time-out errors
```

then the program which outputs to the plotter via COM1 device may be run.

CABLE for IBM/AT to HP7475 plotter:

```
IBM/AT          HP7475

DB9             DB25

2----------------2
3----------------3
5----------------7
8----------------20

1-----|
4-----|
6-----|
```

Graphics During Optimization

The PC versions also use graphics to report the progress of optimization. The appearance of the graphics display is very much the same as described above except that the menu line will look like

K=6   ER=0.0321   Model: FETMDL1   File: C85029A.DAT   <ESC> to interrupt

where K=6 indicates that it is currently the 6th iteration. ER=xxxxx shows the current value of the objective function as defined by (6) or (7) in FORMULATION. The user can interrupt the optimization process by press the <ESC> key. A menu will then be presented to the user:

USER INTERRUPT

Press T to terminate optimization

Or press <CR> to continue

The program will be put on hold, awaiting the user's instruction.

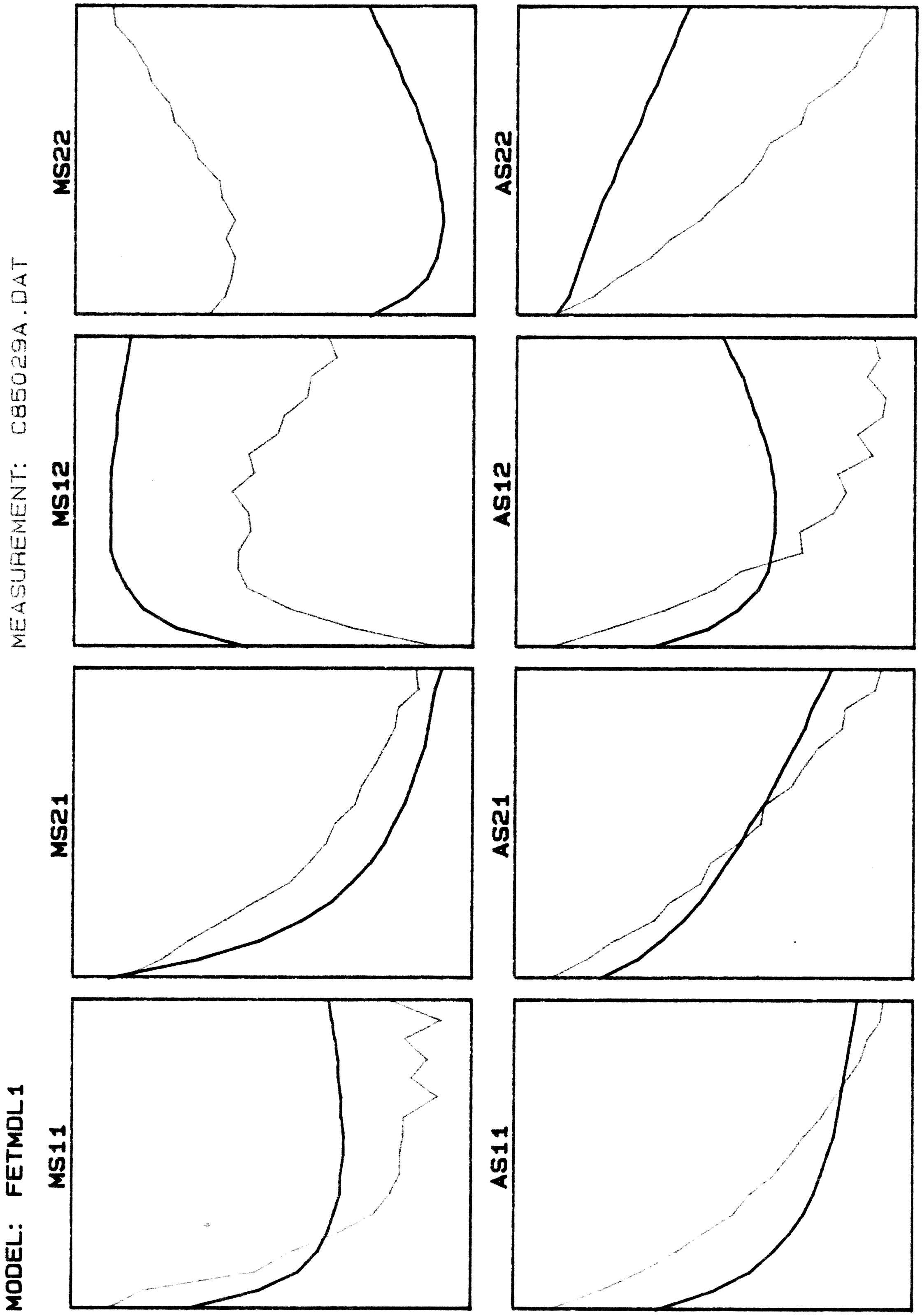


Fig. 1 Measured and modelled responses for C85029A.
Starting point.

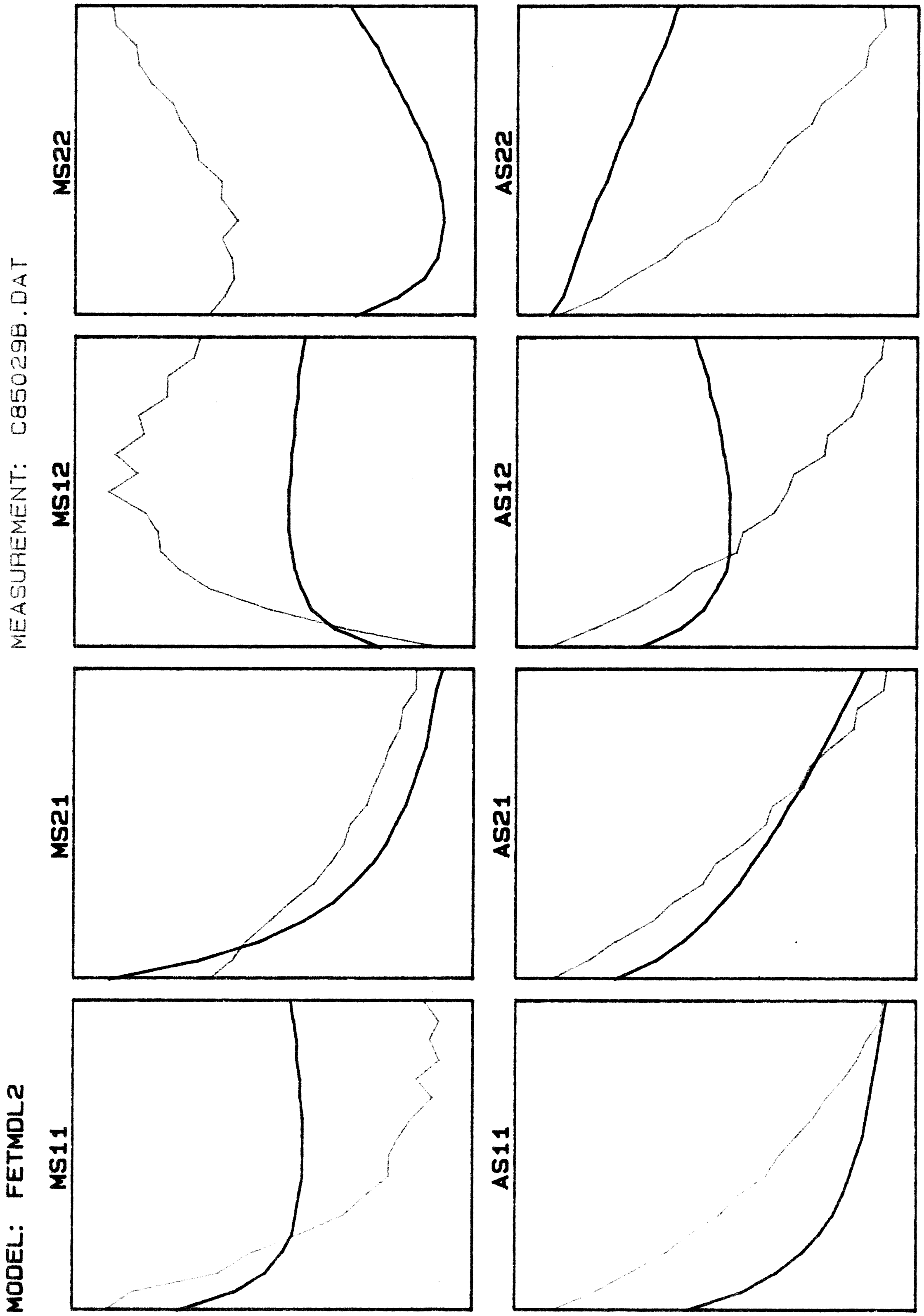


Fig. 2 Measured and modelled responses for C85029B.
Starting point.

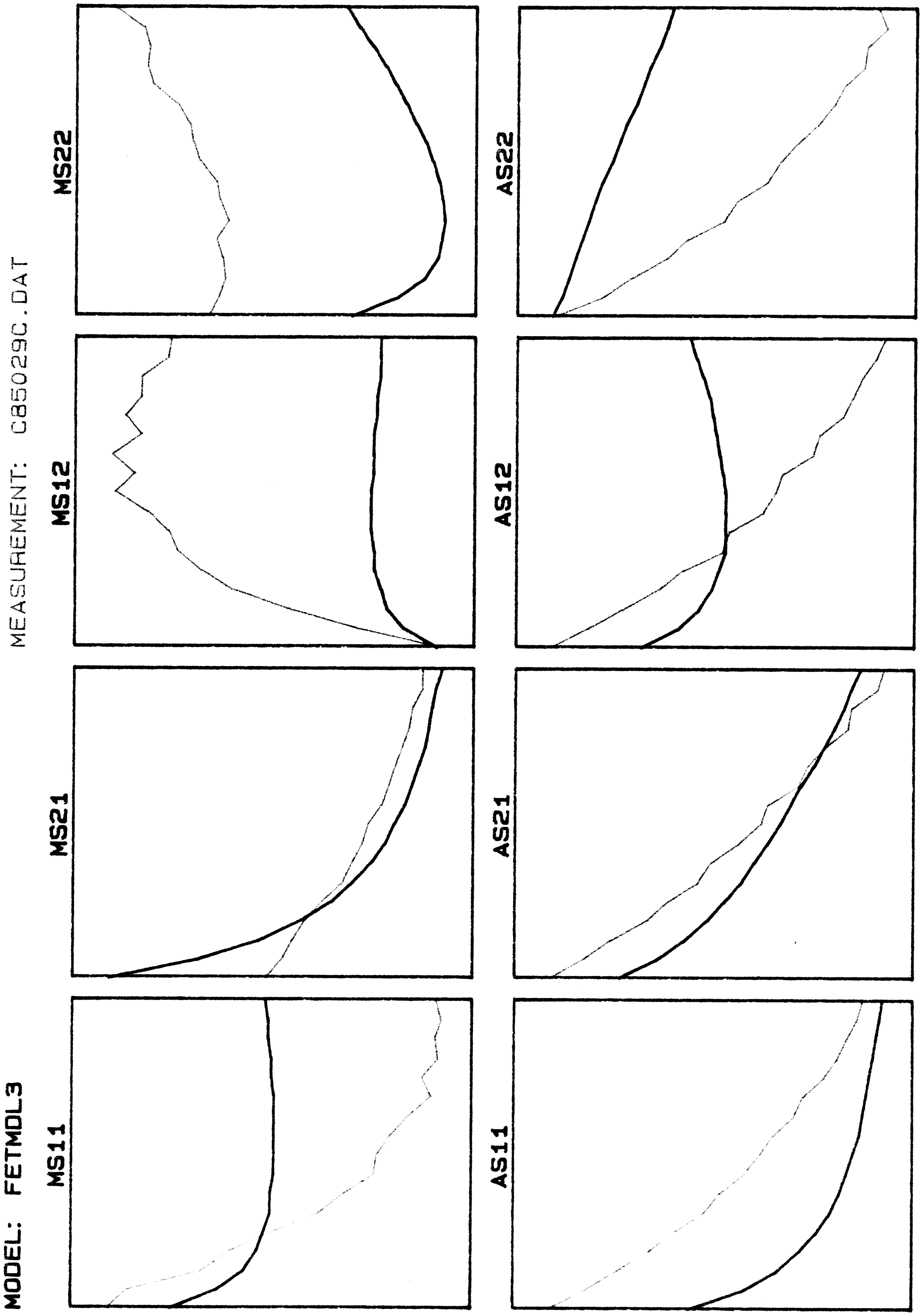


Fig. 3 Measured and modelled responses for C85029C.
Starting point.

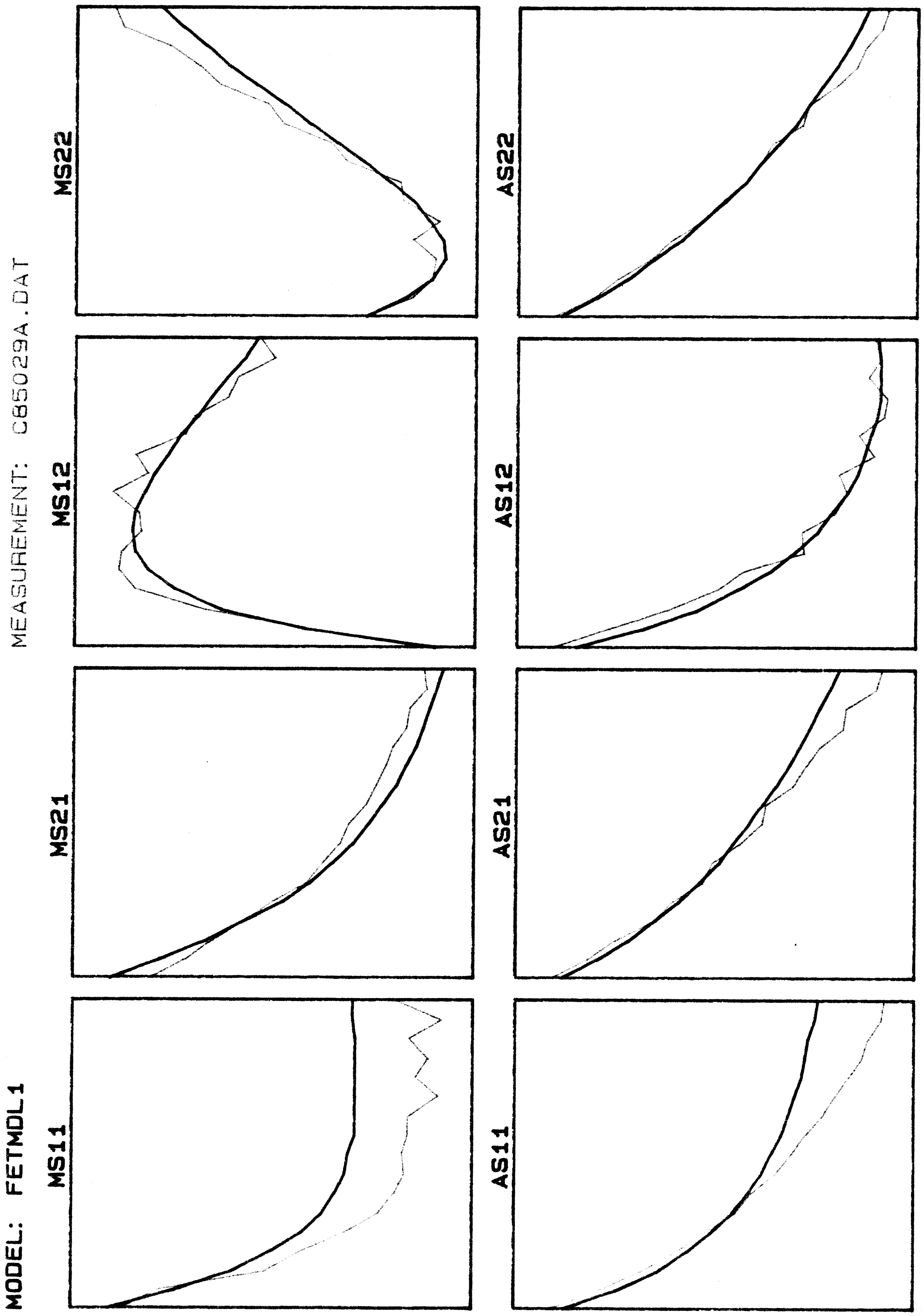


Fig. 4 Measured and modelled responses for C85029A. Simultaneous L_1 optimization is used.

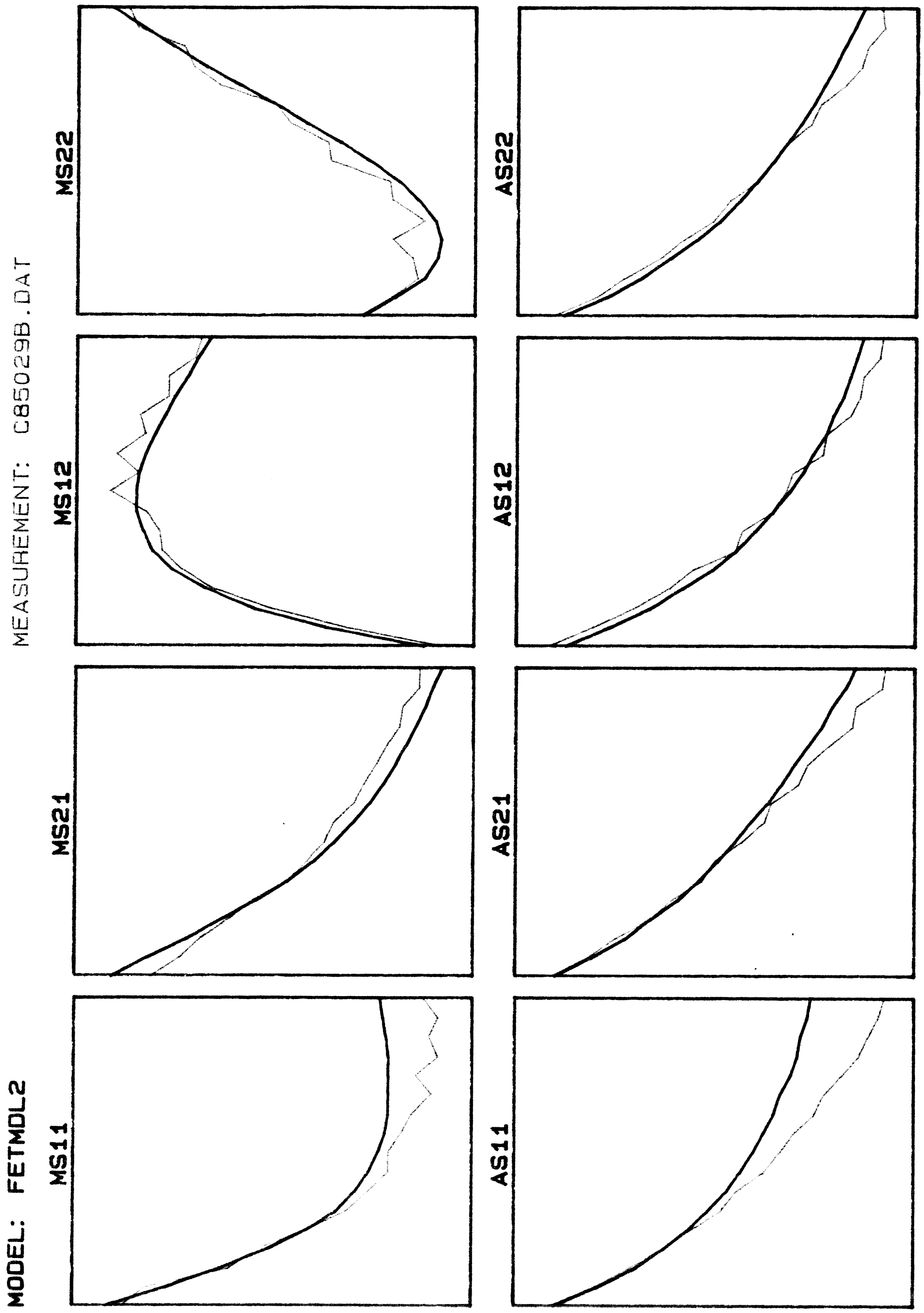


Fig. 5 Measured and modelled responses for C85029B. Simultaneous L_1 optimization is used.

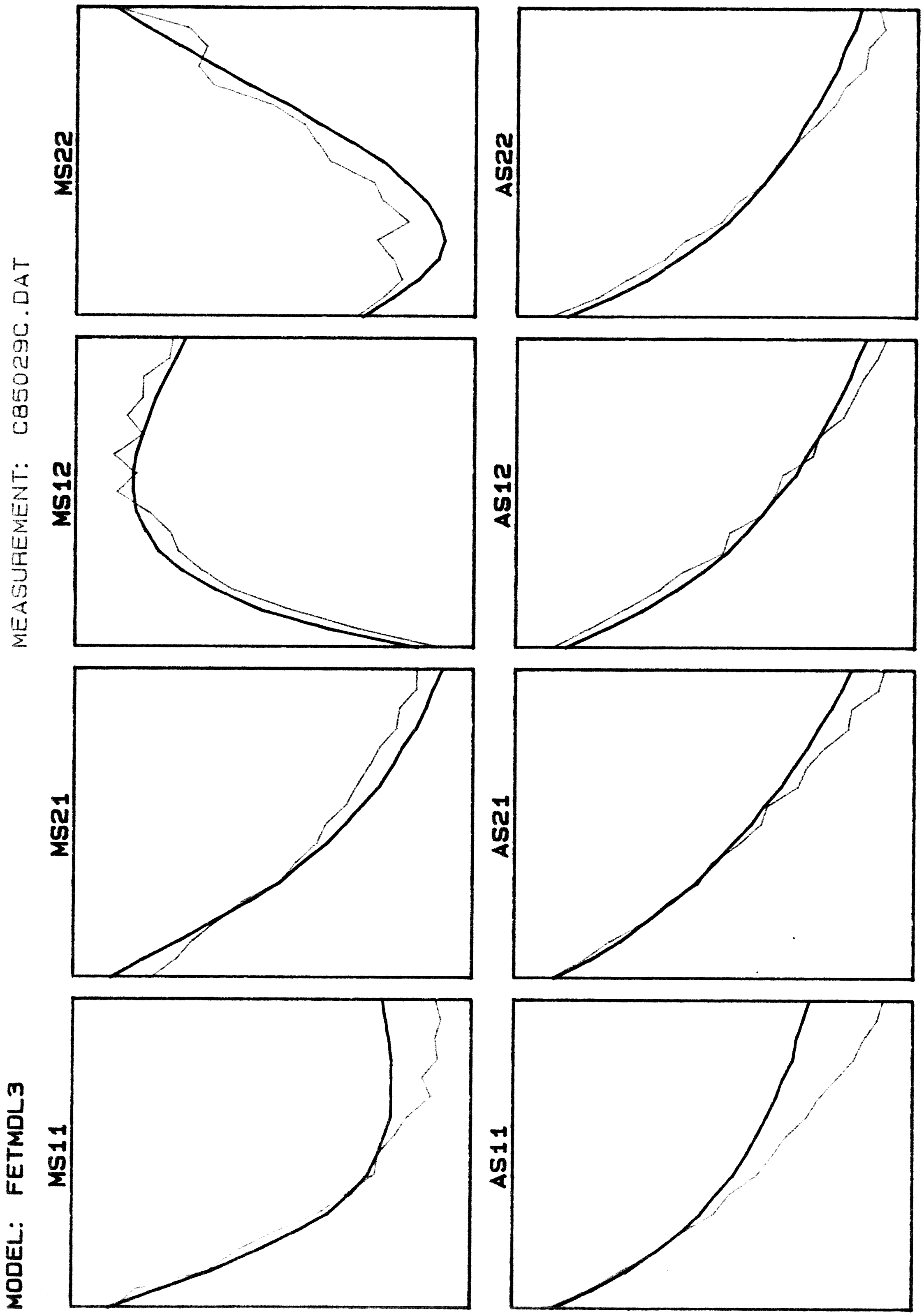


Fig. 6 Measured and modelled responses for C85029C. Simultaneous L_1 optimization is used.

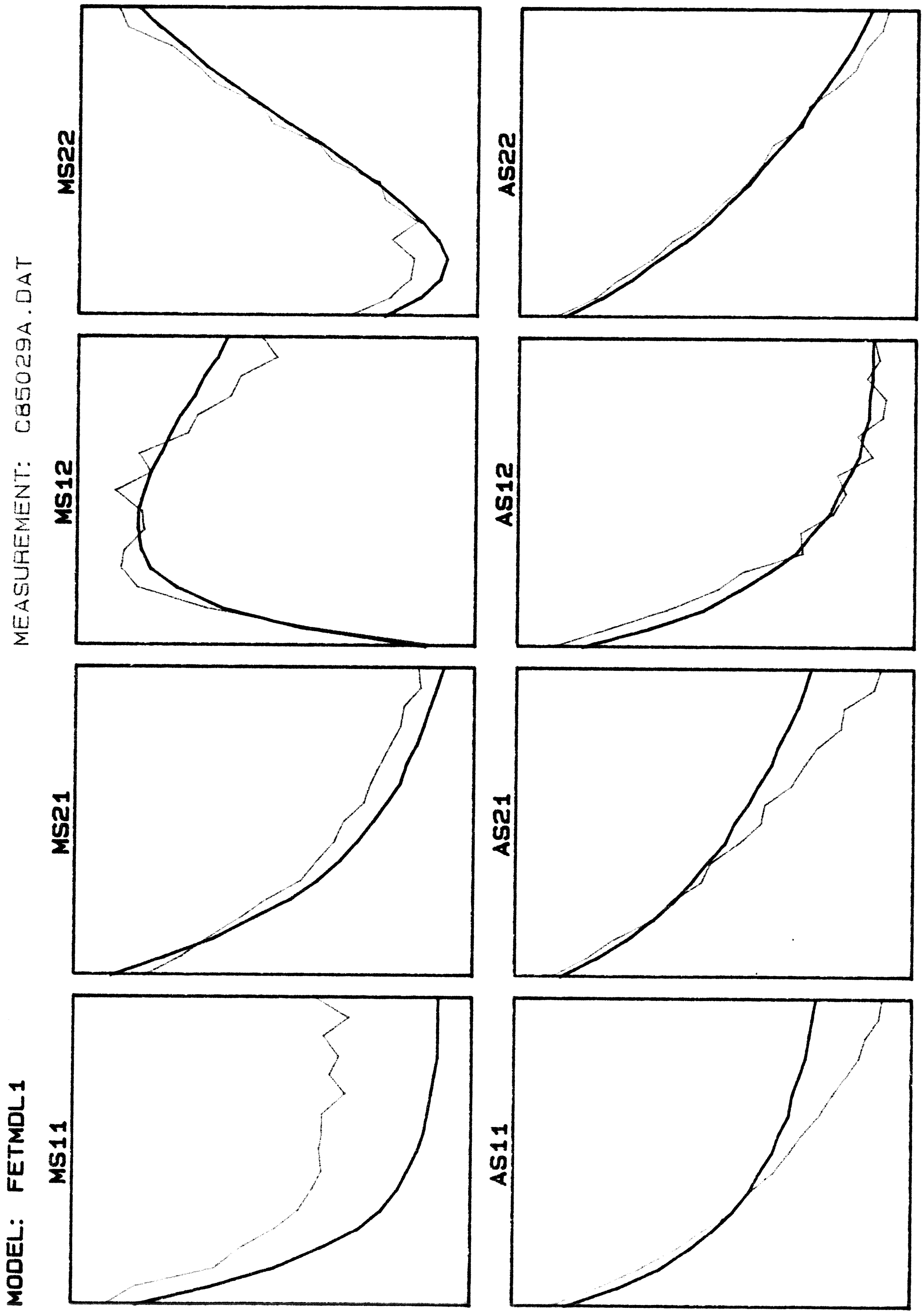


Fig. 7 Measured and modelled responses for C85029A. Simultaneous L_2 optimization is used.

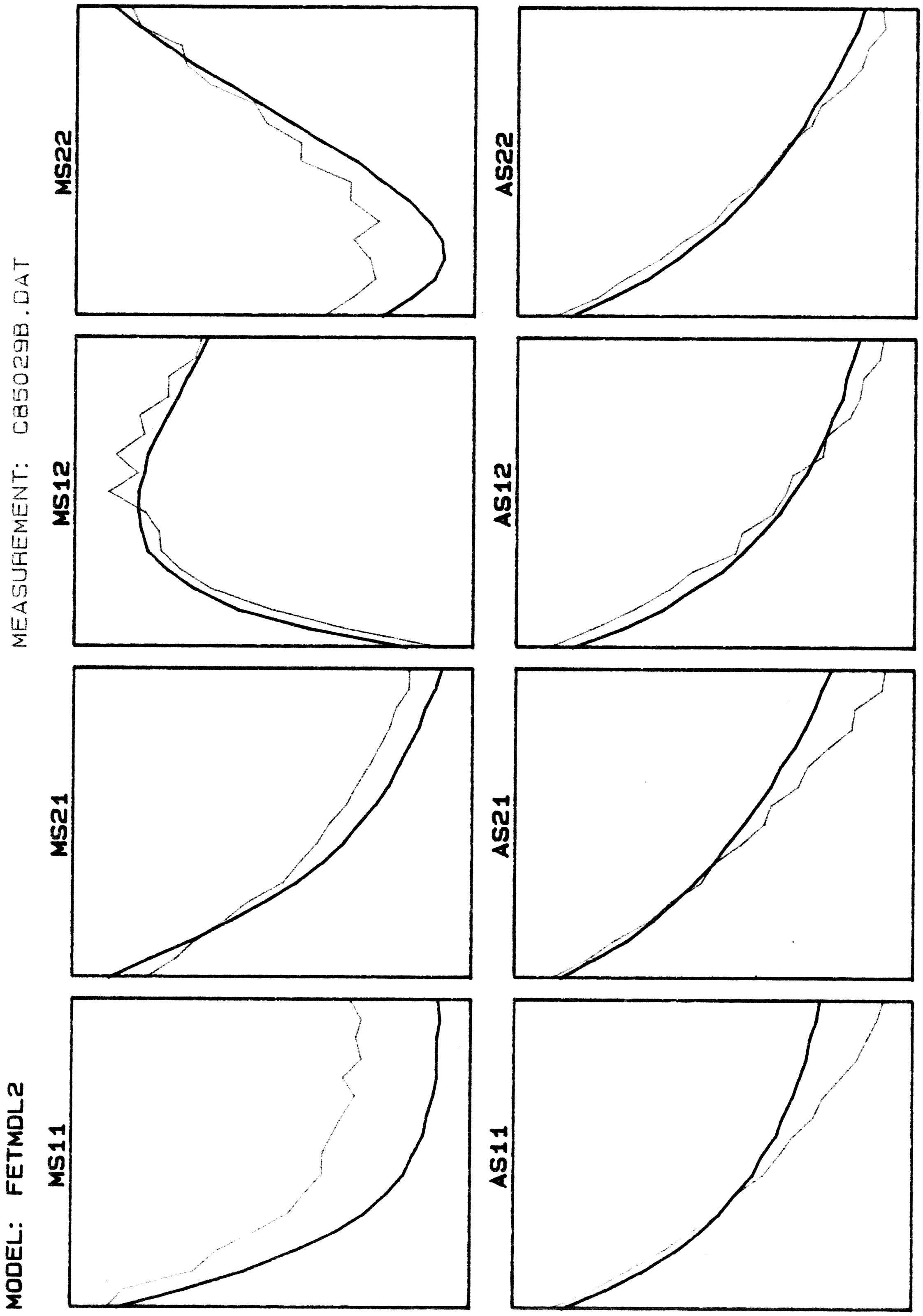


Fig. 8 Measured and modelled responses for C85029B. Simultaneous L_2 optimization is used.

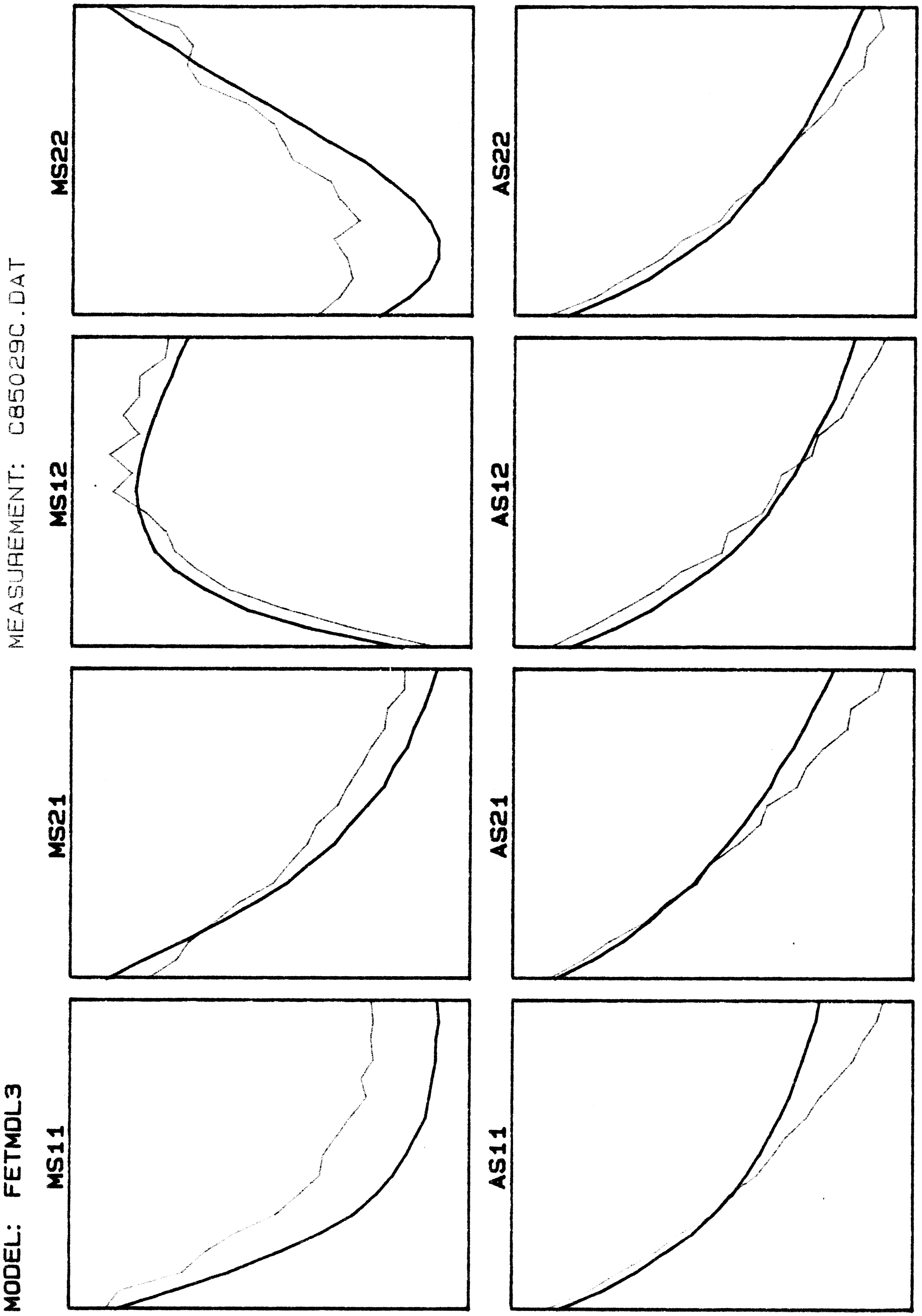
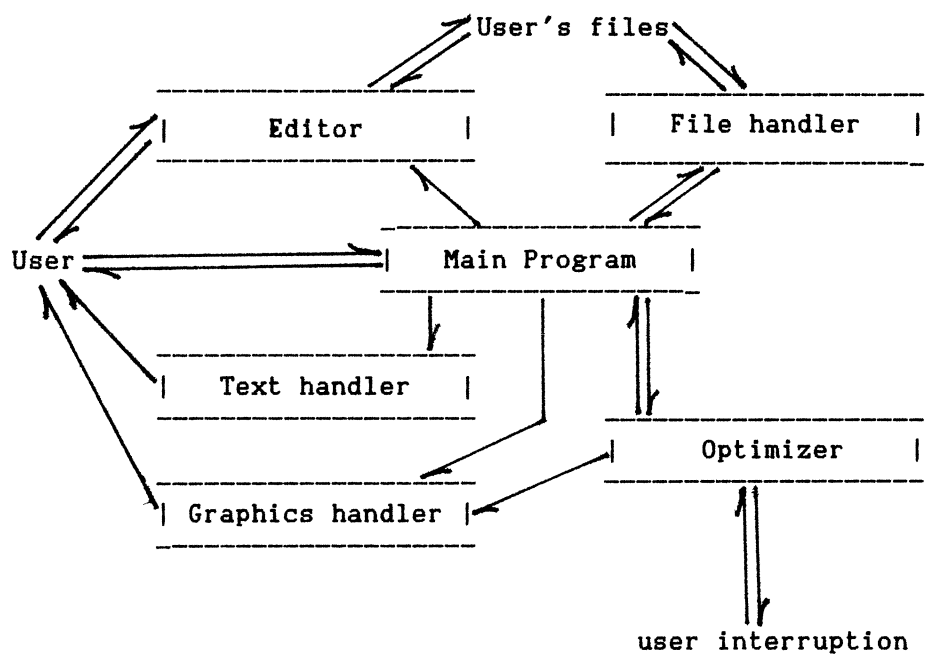


Fig. 9 Measured and modelled responses for C85029C. Simultaneous L_2 optimization is used.

PROGRAM STRUCTURE

Block Structure

Main Program	solicit for user commands and direct operations accordingly
File handler	interpret a SUPERCOMPACT compatible file for circuit definition and optimization directives
Text handler	display information in text format, including menu, parameter values and simulation results
Graphics handler	display S-parameter matching in graphics format
Optimizer	carry out device modelling by optimization
Editor	edit text files on-line



Subroutine Summary

FETSCG or FETSCG1 file - the main program itself and text handling routines:

BRIEF	display the current status (command BRIEFING)
CMPARE	compare starting point and solution (command COMPARE)
FETMDL	program entry, solicit commands, direct operations
FETSIM	organize model simulation sweeping all frequencies
GRAD	display sensitivities (command SENSITIVITY)
HEAD	clear screen, print program heading
HELP	post the main menu
OPTIMI	initiate optimization (commands L1 and L2)
PARSER	interpret commands
SAVCKT	save data to a circuit file (command SAVE)
WDA	display simulation results (commands SWEEP and %ERROR)
WPA	display parameter values (command PARAMETER)

FETFDFG or FETFDFG1 file - simulation handling routines:

CSOLU	solve a set of complex nodal equations
FDF	update variables, provide values of functions and derivatives for the optimizers, handle user interrupt
SIMFET	organize model simulation for one frequency

SCFILE or SCFILE1 file - file handling routines:

BLOCK DATA A	
BLKBLK	interpret BLK block
CHKTYP	check consistency of element types
DATABLK	interpret DATA block
ERMSG	post error messages relating to the circuit file
FERMSG	post error message relating to measurement data files

FREQBLK	interpret FREQ block
GETCHAR	read a non-space character
GETFET	read FET element data
GETFRQ	read a frequency
GETINT	read an integer
GETREAL	read a real number
GETSYMBL	detect special symbols in a line ('=', '?', etc.)
GETUNIT	read data units ('KHZ', 'PF', etc.)
GETVAR	read information of a designated variable
GETWRD	read a word
NODUMMY	detect a comment line
NOSYMBL	detect special symbols in a word
OPTBLK	interpret OPT block
OUTBLK	interpret OUT block (retained for PC compatibility)
PAD	adjust item position by adding spaces
RDCKT	group organizer, also read measurement data file
RDSCF	read circuit file, sort out different blocks

FETPLT or FETPLT1 file - graphics handling routines:

FETPLT	organize data for screen graphics plots
HPPLT	drive a HP plotter for a hardcopy of graphics

L1ABC file - L1 optimization handling routines:

ADDCOL

BFGS

DELCOL

HACCUM

LA1

L1B

L1C L1 optimizer

L1LP

L1STA2

LINSYS

RSOLV

UTRNS

UTTRNS

QUASI2 file - L2 optimization handling routines:

PENALTY

QUASI2 L2 optimizer

CED file - editor:

CED on-line screen editor (written in assembly language)

IBMTXT and IBMGRF files - auxiliary routines in assembly language:

BOX draw a box

CHECKY check keyboard status for user interrupt

CLEAR clear text screen

CLRGRF clear graphics screen

DISP colorful screen positioning and display

KYCODE read a single key stroke

LINE draw a line

MODE set screen mode

PTCOLR set graphics color

RSTSCR restore saved text screen

RSTXOR reset graphics XOR mode

SAVSCR save text screen (before put on graphics)

SETXOR	set graphics XOR mode
STRIM	delete trailing spaces from a line
WINDOW	set graphics display window

Auxiliary Routines in C-language:

SYSTEM	escape path to DOS system for DIR, TYPE commands
SPAWN	escape path to invoke on-line editor

Total number of subroutines: 60

Dimensional Limits

MP model parameters

MX variables

MF frequencies per circuit

8 responses (real and imaginary parts of 4 S-parameters)

3 circuits

250 error functions

The first three limits are controlled by a PARAMETER statement in each subroutine. For FETSCG, it is

```
PARAMETER (MP=11, MX=40, MF=20)
```

For FETSCG1, it is

```
PARAMETER (MP=13, MX=40, MF=20)
```

These limits can be easily modified by editing the PARAMETER statement and the array dimensions will be adjusted automatically.

The last three limits, however, are hard coded. Any attempt to change them is strongly discouraged.

The total number of error functions is given by

$$Ne = \sum_{i=1}^{Nc} \sum_{j=1}^{Nf(i)} Nr(j,i),$$

where

Nc is the total number of circuits,

Nf(i) is the number of frequencies for the ith circuit,

Nr(j,i) is the number of responses at the jth frequency for the ith circuit (the real and imaginary parts of each S-parameters are treated separately).

For example, suppose that we have measurements on all the S-parameters (i.e., 8 responses) at 20 frequencies for 3 circuits. Taking all these data for modelling would result in 3*20*8=480 error functions and, therefore, exceeds the limit on the total number of functions. In this case, we have to reduce the number of frequencies.

Interpreting The Circuit File

Responding to the user's command of 'READ file', subroutine RDSCF reads the specified SUPERCOMPACT compatible file as an ASCII text file and stores the content in the array TT(80,100), where TT(*,i) contains the ith line of the file. Each line may be composed of up to 80 characters and the file may contain up to 100 lines. The actual number of lines read is LINET. Subroutine RDSCF proceeds to sort out different blocks in the file in the following order: 'BLK', 'FREQ', 'OPT', 'DATA' and 'OUT'. The beginning line number of the ith block is recorded in LOCBLK(1,i) and the ending line number in LOCBLK(2,i). If a particular block is missing then LOCBLK(1,i) contains zero.

The content of these blocks are then analyzed by the subroutines in the group 'SC Filer' to produce the following information.

NCKT: total number of circuits

CKTNAME(i): symbolic name of a circuit model (e.g., 'FETMDL1')

CKTFIL(i): name of the file containing a set of measurement data

PA(MP,i): MP model parameters for the ith model

MP=11 for FETSCG and MP=13 for FETSCG1

NX: total number of optimization variables

X(k): value for the kth variable

INPX(j,i): model parameter PA(j,i) <=> variable X(INPX(j,i))

INDX(k): =1: X(k) is unbounded =2: X(k) is bounded

BND(2,k): the lower and upper bounds on X(k)

LOCX(2,k): the line and column position of X(k) in the file

NFR: total number of frequency points

FREQ(j): the jth frequency

WGT(8,j,i): user assigned weights on the 8 measurement data for the jth frequency and the ith circuit. These weights assume the order of RE[S11], IM[S11], etc., as given by the SUPERCOMPACT file specification.

ETERM: user assigned terminating condition for optimization.

Processing The Measurement Data

Having obtained all the essential information from the circuit file, subroutine RDCKT will read the measurement data files whose names have been recorded in CKTFIL(*). The data files are expected to provide 8 S-parameter data in polar form (MAG[S11], ANG[S11], etc.) at all NFR frequencies. Array DAT(8,20,3) is used to store the measurement data. DAT(1,j,i) - DAT(8,j,i) keep the data for the jth frequency and the ith circuit. This is then transformed into the rectangular form (RE[S11], IM[S11], etc.) and stored in DTM(8,20,3).

Interpreting A User's Command

A user's command is read as an ASCII string. Subroutine PARSER compares the input the default commands 'L1', 'L2', 'STOP', 'DIR', 'HELP', 'PARAMETER', 'COMPARE', '%ERROR', 'SWEEP', 'PLOT', 'SENSITIVITY', 'PRESENT', 'BRIEFING', 'SAVE', 'READ', 'EDIT' and 'TYPE'. Only the first two characters are significant. An index KYCD is returned to the main program indicating the position of the input command in the default list. If KYCD is between 1 - 17 then a valid command has been intercepted, e.g., KYCD=4 indicates that the user has entered 'DIR'. KYCD is set to 0 if the user has simply pressed the <ENTER> (<RETURN>) key. KYCD is set to 18 if the user's input is not recognized. The main program acts according to the value of KYCD. The case of KYCD=0 is simply ignored. A warning message is given for KYCD=18. Otherwise, an appropriate subroutine is called for action. Such a mechanism is not hard to understand and the default command list can be modified, e.g., by changing an existing command name or adding a new command. The related subroutines will have to be modified or rewritten, of course.

Organizing Model Simulations

Two subroutines (FETSIM and SIMFET) are responsible for calculating the S-parameter responses of the circuit model. SIMFET accepts a set of parameters (as the formal argument array PA) and a single frequency (formal argument FREQ). In return it provides the model responses in the formal argument F(8) (array F with 8 components) and their sensitivities with respect to the MP parameters in the formal argument DF(8,MP) (MP=11 for FETSCG and MP=13 for FETSCG1). FETSIM organizes simulation for all frequencies.

Feasibility of Substituting FET by Another Model

This program can certainly be modified for other device modelling. The amount of effort needed for such a modification depends on how much the new model differs from the FET model, especially in their circuit topology. The principles are not hard to understand but the actual coding may be frustrated by the requirement for

SUPERCOMPACT file compatibility. Normally, the following steps will have to be taken.

Step 1 Modify the subroutines in the group 'SC Filer' such that the contents of a circuit file relating to the new device can be properly interpreted. All the essential information described in the earlier section should be gathered. Most of the information is not device specific. But, the actual number of parameters and their meaning certainly depend on the particular device of interest.

Step 2 Modify the subroutines responsible for circuit simulation. As explained in the previous section, subroutine SIMFET provides the critical connection. The main program and the optimizers do not know nor care to know the meaning of, say, PA(1) or PA(5). They simply pass the parameters to SIMFET and expect in return the values of the model responses and sensitivities.

Step 3 Modify the subroutines responsible for screen output such that the correct symbols are displayed. Such symbols include phrases like 'FET MODELLING' and names of the parameters ('Rgs', 'Cds', etc.). This should be easy to do.

A Gateway Reserved For the User

Command 'PRESENTATION' provides a convenient gateway for the user to implement operations that are not facilitated by the program. Responding to this command, subroutine PRESENT is called. At the present time, this routine contains nothing but a RETURN statement. To utilize this gateway, a user would substitute the dummy routine with his own subroutine that carries out whatever functions he has in his mind. The following rules must be observed.

Subroutine PRESENT must assume the form

SUBROUTINE PRESENT

Information access is facilitated through common blocks. The names and contents of various arrays have been explained in the earlier sections.

Typically, the user's routine will organize presentations of the data in some customized formats such as printed report. In any case the user must not attempt to modify the data for its consequence would be unpredictable.

The user's codes must be written and compiled using Microsoft FORTRAN version 3.3 or higher. The resulting object code is then linked to the other parts of the program. These 'other parts' include:

FETSCG.OBJ, SCFILE.OBJ, FETFDFG.OBJ, FETPLT.OBJ

for FETSCG, or

FETSCG1.OBJ, SCFILE1.OBJ, FETFDFG1.OBJ, FETPLT1.OBJ

for FETSCG1. The modules that are common to both versions include

L1ABC.OBJ, QUASI2.OBJ, IBMTXT.LIB, IBMGRF.LIB.

The Microsoft libraries FORTRAN.LIB, MATH.LIB (the renamed 8087.LIB) and CEXEC.LIB (C-language interface) should also be available.

Start linking by typing, at the DOS level,

```
C>LINK FETSCG+SCFILE+FETFDFG+L1ABC+QUASI2+FETPLT,,NUL,
       IBMTXT+IBMGRF+CEXEC+FORTRAN+MATH
```

or

```
C>LINK FETSCG1+SCFILE1+FETFDFG1+L1ABC+QUASI2+FETPLT1,,NUL,
       IBMTXT+IBMGRF+CEXEC+FORTRAN+MATH
```

DIFFERENCES BETWEEN FETSCG AND FETSCG1

Two versions of the FET modelling program, namely FETSCG and FETSCG1, are described in this manual. They are implementations of the two different equivalent circuits shown in Figs. 1 and 2. Here, the differences in their actual FORTRAN codes are listed. This also serves to illustrate possible modifications by the user for other models or devices.

The basic modification from FETSCG to FETSCG1 is the inclusion of two inductors LG and LD. As a consequence, the total number of model parameters changes from 11 in FETSCG to 13 in FETSCG1. Therefore, a universal change in the FORTRAN statement

```
PARAMETER (MP=11, MX=40, MF=20)
```

to

```
PARAMETER (MP=13, MX=40, MF=20)
```

is made to each subroutine that contains the statement.

Besides this obvious modification, seven other changes take place in six subroutines as follows. In the source codes of FETSCG1, all the lines that contain these changes have been marked with a special symbol 'CCC' in the first 3 columns.

Main Program

A DATA statement is changed to include indices for LG and LD.

```
FETSCG:         DATA INPO/1,3,4,2,8,9,6,5,7,10,11/
FETSCG1:        DATA INPO/1,3,4,2,8,9,6,5,7,10,11,12,13/
```

Subroutines WPA, CMPARE and GRAD

A DATA statement is changed to include symbols for LG and LD.

FETSCG:

```
      DATA PN/'RG  (OH)','RD  (OH)','GDS(/OH)','RI  (OH)','RS  (OH)',
     *'LS  (nH)','CGS (pF)','CDG (pF)','CDS (pF)','G  (/OH)','T   (ps)'/
```

FETSCG1:

```
      DATA PN/'RG  (OH)','RD  (OH)','GDS(/OH)','RI  (OH)','RS  (OH)',
     *'LS  (nH)','CGS (pF)','CDG (pF)','CDS (pF)','G  (/OH)','T   (ps)',
     *'LG  (nH)','LD  (nH)'/
```

Subroutine GETFET

Two DATA statements are changed to accomodate LG and LD.

FETSCG:

```
      DATA IDP/10,7,6,11,6,8,6,9,3,4,1,2,5,6,6,6,6,6/
      DATA ICO/2,2,1,2,-1,2,0,2,2,2,2,2,2,0,0,0,0,2/
```

FETSCG1:

```
      DATA IDP/10,7,6,11,6,8,6,9,3,4,1,2,5,6,6,12,13,6/
      DATA ICO/2,2,1,2,-1,2,0,2,2,2,2,2,2,0,0,2,2,2/
```

Subroutine SIMFET

The most substantial changes take place in the subroutine SIMFET which is responsible for model simulation. Four groups of lines are modified. The first two groups are related to setting up the admittance matrix (from 1/Rg and 1/Rd to 1/(Rg+sLg) and 1/(Rd+sLd)). The last two groups are related to the sensitivity calculations.

Group 1:

FETSCG:

```
      DO 2 I=1,4
      IF(I.EQ.3)GOTO 2
      IF(PAP(I).GT.1.E-6)THEN
           PAP(I)=1.0/PAP(I)
      ELSE
           PAP(I)=1.E6
      ENDIF
    2 CONTINUE
```

FETSCG1:

```
      I=4
      IF(PAP(I).GT.1.E-6)THEN
           PAP(I)=1.0/PAP(I)
      ELSE
           PAP(I)=1.E6
      ENDIF
```

Group 2:

FETSCG:

```
      DO 20 I=1,4
20    Z(I)=PP(I)
```

FETSCG1:

```
      Z(1)=1.0/(PP(1)+C1*PP(12))
      Z(2)=PP(2)
      Z(3)=1.0/(PP(3)+C1*PP(13))
      Z(4)=PP(4)
```

Group 3:

FETSCG: none (i.e., the following lines are added to FETSCG1)

FETSCG1:

```
      C5=-Z(1)*Z(1)
      C6=-Z(3)*Z(3)
      DO 65 J=1,4
      DZ2P(J,1)=DZ2P(J,1)*C5
      DZ2P(J,12)=DZ2P(J,1)*C1
      DZ2P(J,3)=DZ2P(J,3)*C6
65    DZ2P(J,13)=DZ2P(J,3)*C1
```

Group 4:

FETSCG:

```
      DO 140 I=1,4
      IF(I.EQ.3)GOTO 140
      PR=-PAP(I)*PAP(I)
      DO 130 J=1,8
130   DF(J,I)=DF(J,I)*PR
140   CONTINUE
```

FETSCG1:

```
      I=4
      PR=-PAP(I)*PAP(I)
      DO 130 J=1,8
130   DF(J,I)=DF(J,I)*PR
```