OSA

FET MODELLING USING THE FETSC SYSTEM:

A USER'S GUIDE

OSA–86–FC–7–R

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ABSTRACT

This document provides a user-oriented description of the FETSC software system, which implements 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.

This report follows an earlier version of this software described in Report OSA-86-FC-5-R. The mathematical subprograms are essentially the same. The FETSC system has been developed in Fortran 77 for VAX computers with the VMS operating system, as well as for the IBM/AT with the PC-DOS V3.10 operating system. The program is dedicated to the small-signal FET model in current use at Raytheon. Its execution is not encumbered by features, options and circuit descriptions not directly necessary to the particular FET circuit description. FETSC 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. Data files and corresponding equivalent circuit parameter files can be created, read, edited and/or saved by appropriate user-interaction.

Three versions are presented herein:

(1) a VAX version without graphics called FETSC

(2) a PC version without graphics called FETSC

(3) a PC version with color graphics called FETSCG

All versions use the familiar SUPERCOMPACT form of user-interaction.

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INTRODUCTION

This document reports on the development of a special purpose program for equivalent circuit representation of FETs by optimization using S-parameters. The program 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 program will run on a VAX or an IBM/AT. Data files and corresponding equivalent circuit parameter files can be created, read, edited and/or saved by appropriate user-interaction.

The program, dedicated to the small-signal FET model in current use at Raytheon incorporates state-of-the-art features such as adjoint sensitivity calculations and efficient gradient optimization. Its 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 FETSC (without graphics) and FETSCG (with graphics), 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 FETSC software system is provided. It implements 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].

This report updates an earlier version of this software described in a previous report[3].

The mathematical subprograms are essentially the same. The FETSC system has been developed in Fortran 77 for VAX computers with the VMS operating system, as well as for the IBM/AT with the PC-DOS V3.10 operating system. All versions use the familiar SUPERCOMPACT[4] form of user-interaction.

References

[1] 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.

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

[3] "FET modelling using FETCAD: user's manual and listings," Report OSA-86-FC-5-R, July 4, 1986.

[4] 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 Circuit

The proposed equivalent circuit is shown in Fig. 1. As
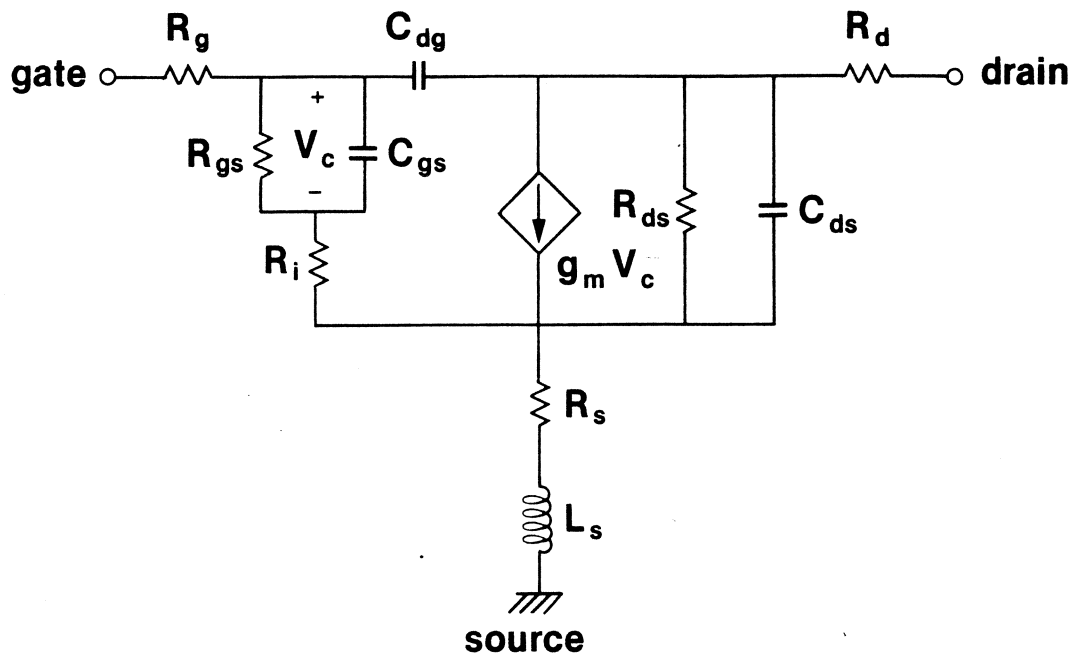
$$y_m = \frac{g_m * e^{-j2\pi f \tau}}{1 + j(f/f_{3dB})}$$

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

Fig. 1   The equivalent circuit of the FET.

illustrated in Fig. 1, there is a total of 11 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. Any or all of these 11 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:

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

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.

The L_1 Optimization

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 $S_{ij}^m(k)$, $i = 1,2$, $j = 1,2$, $k = 1,2,\ldots, n_f$, where S_{ij} is the complex S-parameter and m is used to denote the measured response. Similarly, we have $S_{ij}^c(k)$, where c is used to denote the calculated response using the equivalent circuit parameters. $S_{ij}^c(k)$ is a function of circuit parameters, and as mentioned before, we seek optimum circuit parameters such that $S_{ij}^c(k)$ best approximates $S_{ij}^m(k)$.

We define the unweighted error functions as

$$FR_{ij}(k) = Re[S_{ij}^m(k)] - Re[S_{ij}^c(k)], \tag{2}$$

$$FI_{ij}(k) = Im[S_{ij}^m(k)] - Im[S_{ij}^c(k)], \tag{3}$$

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

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

and

$$NWI_{ij} = W_{ij}/(\max_k\{Im[S^m_{ij}(k)]\} - \min_k\{Im[S^m_{ij}(k)]\}). \qquad (5)$$

The L_1 objective function is defined as

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

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

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

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

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

where

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

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 FETSC system is given. The reader is referred to the SUPERCOMPACT user's manual[1] for further guidelines.

Blocks

The following blocks provide information relevant to FETSC and FETSCG 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.

The OUT block directing graphics output is optional to FETSCG. It may be present in FETSC but will not be interpreted.

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

Comments

Comments placed in a file must be preceded by the special symbol '*'.

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 with the special equivalent circuit used in this report (Fig. 1) is the only element type permitted in a FETSC or
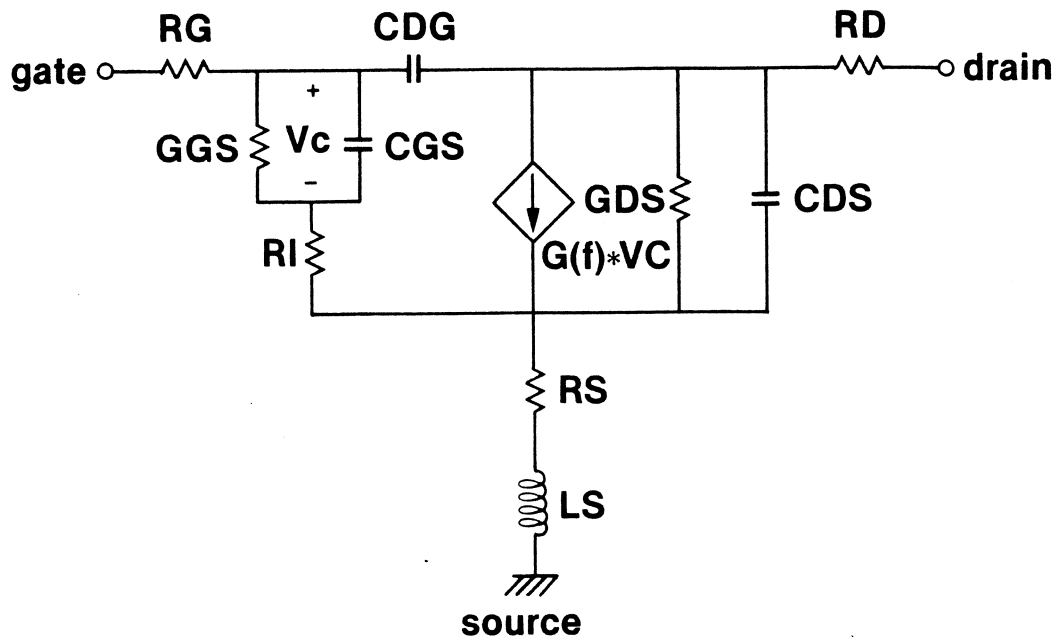
$$G(f) = \frac{G \star e^{-j2\pi fT}}{1 + j(f/F)}$$

$$F = 1000 \text{ GHz}$$

Fig. 1   The equivalent circuit of the FET.

FETSCG file because it is the only device meaningful to these packages in their present form.   Defining any other elements such as RES, CAP, etc., will result in an error.   The general form 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 nl and n2 are node numbers. The ground node 0 is optional. The xl to x13 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 nl n2 [0]

Model_name is an arbitrary name having 1 - 8 characters and followed immediately by ':'. The nl 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 FETSC or FETSCG.

'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 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 FETSC

The operation of the FETSC package on a VAX is demonstrated with the help of two examples. The first involves a single circuit and the other involves three circuits.

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

Start the operation on the VAX by keying in the command

$ RUN FETSC

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

Creating a Circuit File, READ and TYPE

Using the VAX full screen editor, we create a SUPERCOMPACT compatible circuit file called ONECKT.DAT. After creating this file, we are back at the command level of FETSC 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 and %ERROR

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.

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 VMS
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
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>
 Input : ED ONECKT.DAT
          V A X      E D T      E D I T O R

COMD>
 Input : TYPE ONECKT.DAT

*Single measurement C85029A
BLK
*
        G1:?0.09?
        T1:?0.007NS?
        C1:?1.4PF?
        C2:?0.07PF?
        C3:?0.4PF?
        G2:?0.007?
        R1:?1?
        R2:?1?
        R3:?1?
        R4:?1?
        L1:?0.02NH?
        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>
 Input : READ ONECKT
     Reading circuit file...

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

```
COMD>
 Input : 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>
 Input : 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>
 Input : PA
         FET MODEL PARAMETERS
           FETMDL1
           1.00000       RG   (OH)
           1.00000       RD   (OH)
           0.00700       GDS(/OH)
           1.00000       RI   (OH)
           1.00000       RS   (OH)
           0.02000       LS   (nH)
           1.40000       CGS  (pF)
           0.07000       CDG  (pF)
           0.40000       CDS  (pF)
           0.09000       G    (/OH)
           7.00000       T    (ps)
```

COMD>
 Input : %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	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>
 Input : L1

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

     Start modelling ...
     You can press any key to interrupt optimization

     Iteration 1   L1 error   2.4215007
     Iteration 2   L1 error   1.7039427
     Iteration 3   L1 error   0.7347444
     Iteration 4   L1 error   0.5093994
     Iteration 5   L1 error   0.4990287
     Iteration 6   L1 error   0.4524295
     Iteration 7   L1 error   0.4492849
     Iteration 8   L1 error   0.4481698
     Iteration 9   L1 error   0.4477605
     Iteration 10   L1 error   0.4477171
     Iteration 11   L1 error   0.4475315
     Iteration 12   L1 error   0.4476416
     Iteration 13   L1 error   0.4474366

```
     Optimization Completed
     13 iterations      3.13 CPU seconds
        FET MODEL PARAMETERS
          FETMDL1
        starting        solution
        1.00000         3.06508   RG  (OH)
        1.00000         3.07341   RD  (OH)
        0.00700         0.00506   GDS(/OH)
        1.00000         0.01378   RI  (OH)
        1.00000         0.94576   RS  (OH)
        0.02000         0.00490   LS  (nH)
        1.40000         0.67515   CGS (pF)
        0.07000         0.03033   CDG (pF)
        0.40000         0.22060   CDS (pF)
        0.09000         0.06727   G   (/OH)
        7.00000         4.74326   T   (ps)
```

```
COMD>
 Input : SAVE ONECKTL1
COMD>
 Input : CO
        FET MODEL PARAMETERS
          FETMDL1
        starting        solution
        1.00000         3.06508   RG  (OH)
        1.00000         3.07341   RD  (OH)
        0.00700         0.00506   GDS(/OH)
        1.00000         0.01378   RI  (OH)
        1.00000         0.94576   RS  (OH)
        0.02000         0.00490   LS  (nH)
        1.40000         0.67515   CGS (pF)
        0.07000         0.03033   CDG (pF)
        0.40000         0.22060   CDS (pF)
        0.09000         0.06727   G   (/OH)
        7.00000         4.74326   T   (ps)
```

COMD>
 Input : %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   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>
 Input : 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>
 Input : BR

    Working file: ONECKTL1.DAT
    Number of circuits: 1
    Measurement files: C85029A.DAT
COMD>
 Input : READ ONECKT
     Reading circuit file...

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

COMD>
 Input : L2

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

       Start modelling ...
       You can press any key to interrupt optimization

       Iteration 1   L2 error   1.4328918
       Iteration 2   L2 error   0.8403827
       Iteration 3   L2 error   0.2060595
       Iteration 4   L2 error   0.1863935
       Iteration 5   L2 error   0.0936570
       Iteration 6   L2 error   0.8809951
       Iteration 7   L2 error   0.0839897
       Iteration 8   L2 error   0.1306155
       Iteration 9   L2 error   0.0819032
       Iteration 10   L2 error   0.0735486
       Iteration 11   L2 error   0.0929332
       Iteration 12   L2 error   0.0703869
       Iteration 13   L2 error   0.0701839
       Iteration 14   L2 error   0.0693486
       Iteration 15   L2 error   0.0687101
       Iteration 16   L2 error   0.0844100
       Iteration 17   L2 error   0.0656381
       Iteration 18   L2 error   0.0653310
       Iteration 19   L2 error   0.0652332
       Iteration 20   L2 error   0.0651622
       Iteration 21   L2 error   0.0651320
       Iteration 22   L2 error   0.0650604
       Iteration 23   L2 error   0.0649676
       Iteration 24   L2 error   0.0648164
       Iteration 25   L2 error   0.0646840
       Iteration 26   L2 error   0.0646226
       Iteration 27   L2 error   0.0646112
       Iteration 28   L2 error   0.0646054
       Iteration 29   L2 error   0.0646000
       Iteration 30   L2 error   0.0645970
       Iteration 31   L2 error   0.0645935
       Iteration 32   L2 error   0.0645874
       Iteration 33   L2 error   0.0645783
       Iteration 34   L2 error   0.0645692
       Iteration 35   L2 error   0.0645625
       Iteration 36   L2 error   0.0645594
       Iteration 37   L2 error   0.0645563
       Iteration 38   L2 error   0.0645509
       Iteration 39   L2 error   0.0645426
       Iteration 40   L2 error   0.0645339
       Iteration 41   L2 error   0.0645062
       Iteration 42   L2 error   0.0644917
       Iteration 43   L2 error   0.0644822
       Iteration 44   L2 error   0.0644768
       Iteration 45   L2 error   0.0644759

```
Iteration 46      L2 error     0.0644750
Iteration 47      L2 error     0.0644741
Iteration 48      L2 error     0.0644712
Iteration 49      L2 error     0.0644671
Iteration 50      L2 error     0.0644613
Iteration 51      L2 error     0.0644560
Iteration 52      L2 error     0.0644522
Iteration 53      L2 error     0.0644510
Iteration 54      L2 error     0.0644480
Iteration 55      L2 error     0.0644470
Iteration 56      L2 error     0.0644462
Iteration 57      L2 error     0.0644450
Iteration 58      L2 error     0.0644438
Iteration 59      L2 error     0.0644427
Iteration 60      L2 error     0.0644416
Iteration 61      L2 error     0.0644410
Iteration 62      L2 error     0.0644404
Iteration 63      L2 error     0.0644403
Iteration 64      L2 error     0.0644400
Iteration 65      L2 error     0.0644401
Iteration 66      L2 error     0.0644401
Iteration 67      L2 error     0.0644401


Optimization Completed
 67 iterations        5.85 CPU seconds
     FET MODEL PARAMETERS
        FETMDL1
 starting         solution
 1.00000          4.94463   RG  (OH)
 1.00000          1.81533   RD  (OH)
 0.00700          0.00542   GDS(/OH)
 1.00000          0.01070   RI  (OH)
 1.00000          1.05717   RS  (OH)
 0.02000          0.00448   LS  (nH)
 1.40000          0.73919   CGS (pF)
 0.07000          0.03238   CDG (pF)
 0.40000          0.21633   CDS (pF)
 0.09000          0.06984   G   (/OH)
 7.00000          3.51992   T   (ps)
```

```
COMD>
 Input : SE
        SENSITIVITY OF THE CURRENT MODEL
        least-squares error:     0.06444001
          FETMDL1
          gradient
          0.011226     RG   (OH)
          0.001489     RD   (OH)
          0.006218     GDS(/OH)
          0.000012     RI   (OH)
         -0.005936     RS   (OH)
         -0.001443     LS   (nH)
          0.053245     CGS  (pF)
          0.019829     CDG  (pF)
          0.008137     CDS  (pF)
         -0.031499     G    (/OH)
         -0.009962     T    (ps)


COMD>
 Input : %ER
```

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

Frequency (GHZ)	model: FETMDL1				measurement: C85029A.DAT			
	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	1.31%	15.87%	8.92%	3.59%	6.48%	8.75%	4.44%	17.30%
3.0	4.22%	11.52%	5.28%	3.45%	3.37%	13.25%	3.99%	7.20%
4.0	3.31%	9.02%	2.15%	5.39%	0.24%	14.51%	4.13%	9.70%
5.0	4.52%	5.35%	5.10%	1.26%	3.51%	13.20%	4.16%	5.07%
6.0	4.52%	3.71%	8.08%	2.87%	2.21%	16.43%	5.19%	6.38%
7.0	4.48%	0.28%	7.42%	2.21%	0.53%	7.31%	1.60%	1.93%
8.0	4.74%	0.72%	10.72%	1.61%	2.51%	13.57%	2.35%	2.84%
9.0	4.95%	4.14%	13.33%	5.68%	1.52%	6.87%	0.44%	0.42%
10.0	5.60%	4.96%	17.05%	11.12%	3.47%	10.20%	1.69%	1.54%
11.0	5.71%	6.50%	15.53%	6.70%	0.02%	19.93%	0.49%	2.86%
12.0	5.97%	7.99%	19.41%	18.55%	3.43%	41.14%	1.16%	1.89%
13.0	4.66%	9.63%	19.93%	23.53%	1.37%	12.20%	0.12%	0.61%
14.0	5.98%	11.05%	21.76%	33.22%	0.61%	60.70%	0.82%	3.34%
15.0	5.37%	12.86%	19.99%	68.63%	3.62%	69.18%	0.01%	4.87%
16.0	6.43%	13.14%	24.51%	58.14%	2.56%	8.44%	0.07%	3.82%
17.0	4.82%	14.80%	15.60%	187.85%	6.99%	34.23%	0.99%	5.42%
18.0	7.12%	14.31%	24.42%	277.61%	1.49%	18.48%	0.05%	4.13%

```
COMD>
 Input : SAVE ONECKTL2
COMD>
 Input : STOP
```

Multi-Circuit Example

A powerful feature of the FETSC package 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 FETSC with multiple circuits. The results will prove the robustness of the package in terms of the choice of starting values and the frequency points.

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	C85029A.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.

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.

Reduced Sample Points

We now perform two tests to demonstrate the robustness of the FETSC package.   In the first test, we solve the above multi-circuit problem using half the frequency points as used before, i.e., we use S-parameter measurements from 2 to 18 GHz with a 2 GHz increment. In TEST1.DAT file, only the increment in the FREQ block has been changed compared to the ALLTHREE.DAT.   Consistency of the results obtained using half the frequencies with the previous results provides more confidence in the validity of circuit parameters.   The reduction in CPU time is significant.   We can usually expect an almost linear reduction in the CPU time as the number of frequency points is reduced.

Different Starting Points

In a second test, we examine the robusness of the package in dealing with different starting values.   In TEST2.DAT file (which has been listed with the TYPE command) the starting values have been changed to the rather arbitrary numbers shown.   Parameters obtained after performing the L1 optimization are consistent with the previous

results. We tried at least 20 different sets of arbitrary starting

values and came up with approximately the same results in all cases

except when the starting values were extremely wild. It should be

mentioned that all the software packages for FET modelling that we

know are sensitive (especially, some parameters such as the resistors)

to the choice of starting values.   We compare the performance of

FETSC to the popular COMPACT software system in a separate section.

```
COMD>
 Input : ED ALLTHREE.DAT
         V A X        E D T       E D I T O R

COMD>
 Input : TYPE ALLTHREE.DAT

*All three measurements C85029A, C85029B and C85029C
BLK
*        common variables
         RO:2.E-6
         FO: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=FO T=TAU GGS=RO 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=FO T=TAU GGS=RO 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=FO T=TAU GGS=RO 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 1.0GHZ
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>
 Input : READ ALLTHREE
     Reading circuit file...

    Working file: ALLTHREE.DAT
    Number of circuits: 3
    Measurement files: C85029A.DAT   C85029B.DAT   C85029C.DAT
COMD>
 Input : 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>
 Input : L1

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

       Start modelling ...
       You can press any key to interrupt optimization

       Iteration  1     L1 error    2.6496809
       Iteration  2     L1 error    2.0904052
       Iteration  3     L1 error    1.3958710
       Iteration  4     L1 error    0.7056876
       Iteration  5     L1 error    0.8660346
       Iteration  6     L1 error    0.5506932
       Iteration  7     L1 error    0.5429597
       Iteration  8     L1 error    0.5097529
       Iteration  9     L1 error    0.5062686
       Iteration 10     L1 error    0.5027795
       Iteration 11     L1 error    0.4986020
       Iteration 12     L1 error    0.4980656
       Iteration 13     L1 error    0.4978623
       Iteration 14     L1 error    0.4978395
       Iteration 15     L1 error    0.4976631
       Iteration 16     L1 error    0.4979259
       Iteration 17     L1 error    0.4980634
       Iteration 18     L1 error    0.4982309
       ιteration 19     L1 error    0.4979310


       Optimization Completed
        19 iterations      43.09 CPU seconds
          FET MODEL PARAMETERS
         FETMDL1              FETMDL2              FETMDL3
   starting  solution   starting  solution   starting  solution
     1.0000    2.5487     1.0000    2.5487     1.0000    2.5487   RG  (OH)
     1.0000    3.7457     1.0000    3.7457     1.0000    3.7457   RD  (OH)
     0.0070    0.0050     0.0070    0.0061     0.0070    0.0061   GDS(/OH)
     1.0000    0.0000     1.0000    0.1715     1.0000    0.4776   RI  (OH)
     1.0000    1.0042     1.0000    0.9077     1.0000    0.6243   RS  (OH)
     0.0200    0.0039     0.0200    0.0039     0.0200    0.0039   LS  (nH)
     1.4000    0.7224     1.4000    0.4414     1.4000    0.3451   CGS (pF)
     0.0700    0.0306     0.0700    0.0476     0.0700    0.0610   CDG (pF)
     0.0400    0.2227     0.0400    0.2227     0.0400    0.2148   CDS (pF)
     0.0900    0.0698     0.0900    0.0520     0.0900    0.0409   G   (/OH)
     7.0000    3.9600     7.0000    3.9600     7.0000    3.9600   T   (ps)
```

COMD>
 Input : %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	0.74%	14.04%	11.72%	2.99%	2.06%	6.97%	0.04%	12.93%
3.0	0.69%	10.06%	9.01%	2.83%	0.26%	10.88%	0.45%	3.88%
4.0	1.60%	7.89%	2.12%	4.95%	2.52%	12.01%	0.02%	6.89%
5.0	1.37%	4.47%	0.45%	1.12%	5.25%	10.93%	0.59%	2.82%
6.0	2.15%	2.95%	3.30%	3.13%	3.51%	14.31%	2.25%	4.41%
7.0	2.80%	0.91%	2.43%	1.45%	1.72%	8.70%	0.77%	0.33%
8.0	2.97%	1.29%	5.86%	2.87%	1.51%	12.89%	0.65%	1.44%
9.0	3.11%	4.64%	8.62%	3.71%	0.49%	4.91%	0.65%	0.73%
10.0	2.67%	5.42%	12.59%	8.33%	4.36%	6.84%	1.21%	0.55%
11.0	2.81%	6.92%	11.07%	3.26%	1.07%	26.24%	0.56%	2.01%
12.0	2.70%	8.38%	15.27%	13.79%	4.41%	26.74%	1.74%	2.57%
13.0	4.28%	10.00%	15.93%	17.47%	0.34%	23.26%	0.94%	0.03%
14.0	2.96%	11.40%	17.97%	25.37%	0.43%	36.80%	2.30%	3.80%
15.0	3.72%	13.19%	16.24%	56.79%	2.52%	40.72%	1.90%	5.24%
16.0	2.65%	13.45%	21.09%	44.99%	1.43%	25.17%	2.18%	4.13%
17.0	4.54%	15.11%	11.92%	159.57%	5.61%	2.76%	3.53%	5.66%
18.0	2.07%	14.61%	21.25%	233.79%	0.11%	14.69%	2.93%	4.33%

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	0.80%	6.71%	10.27%	1.70%	7.34%	4.97%	0.31%	16.17%
3.0	1.09%	3.38%	9.39%	1.38%	5.57%	7.66%	0.20%	7.42%
4.0	0.56%	3.29%	4.22%	3.38%	3.99%	9.77%	0.33%	10.23%
5.0	0.56%	0.05%	1.89%	0.37%	1.16%	8.79%	2.03%	5.61%
6.0	0.03%	0.40%	0.66%	1.70%	1.59%	13.60%	3.72%	6.85%
7.0	0.80%	4.15%	0.08%	1.56%	1.66%	2.29%	0.72%	1.82%
8.0	0.83%	3.93%	2.66%	1.45%	3.19%	16.07%	2.09%	2.98%
9.0	1.34%	7.40%	4.99%	2.94%	1.42%	2.21%	0.63%	0.11%
10.0	0.69%	8.07%	8.88%	7.43%	4.45%	3.41%	2.73%	0.04%
11.0	1.10%	9.05%	7.85%	1.66%	0.36%	28.54%	0.81%	0.16%
12.0	1.60%	10.84%	10.81%	11.34%	5.27%	316.63%	1.07%	2.90%
13.0	2.85%	11.76%	12.38%	10.68%	1.93%	2.04%	0.03%	1.81%
14.0	1.81%	13.65%	13.43%	17.55%	4.70%	63.28%	1.23%	4.75%
15.0	3.45%	15.09%	12.69%	33.38%	1.35%	49.49%	0.92%	6.80%
16.0	3.08%	15.69%	16.29%	24.81%	3.74%	36.16%	0.60%	5.20%
17.0	4.02%	16.89%	12.89%	68.44%	0.80%	43.43%	0.25%	7.51%
18.0	2.93%	16.53%	17.57%	54.59%	1.95%	37.92%	0.81%	4.14%

Press any key to continue ...

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

Frequency (GHZ)	model: FETMDL3				measurement: C85029C.DAT			
	MS11	AS11	MS21	AS21	MS12	AS12	MS22	AS22
2.0	0.49%	6.40%	9.97%	1.60%	12.08%	5.46%	0.37%	18.82%
3.0	1.58%	2.72%	9.22%	1.30%	10.19%	8.40%	0.61%	9.03%
4.0	0.18%	3.29%	4.24%	3.24%	8.04%	10.59%	1.27%	12.51%
5.0	1.42%	0.31%	1.74%	0.48%	4.47%	9.78%	2.96%	7.14%
6.0	1.56%	0.58%	1.28%	1.61%	4.49%	15.70%	4.42%	8.54%
7.0	0.55%	4.56%	0.22%	1.63%	4.28%	2.86%	2.14%	2.50%
8.0	0.13%	4.15%	2.39%	1.37%	5.17%	18.99%	2.92%	4.05%
9.0	0.72%	7.84%	4.70%	2.77%	2.90%	2.87%	2.32%	0.07%
10.0	0.05%	8.59%	9.02%	7.24%	3.25%	8.51%	3.33%	0.51%
11.0	0.65%	9.27%	7.81%	1.68%	0.66%	34.41%	2.25%	0.50%
12.0	1.49%	11.45%	10.71%	11.49%	4.66%	307.50%	1.00%	2.79%
13.0	3.28%	11.96%	11.73%	10.13%	0.01%	17.51%	0.93%	4.55%
14.0	2.48%	14.24%	13.43%	16.68%	4.33%	43.85%	2.17%	4.77%
15.0	3.87%	15.54%	12.37%	30.95%	2.68%	34.82%	1.16%	7.14%
16.0	3.77%	16.37%	15.77%	24.25%	4.62%	26.53%	1.42%	5.33%
17.0	4.60%	17.34%	11.91%	63.17%	1.01%	31.77%	2.30%	7.71%
18.0	4.60%	17.38%	16.39%	54.19%	2.68%	28.28%	0.12%	4.24%

COMD>
 Input : SE

SENSITIVITY OF THE CURRENT MODEL
least-squares error: 0.08651762

FETMDL1	FETMDL2	FETMDL3		
gradient	gradient	gradient		
-0.001881	-0.003091	-0.003176	RG	(OH)
0.000651	-0.000476	-0.000407	RD	(OH)
-0.006294	-0.007466	-0.005322	GDS	(/OH)
0.000000	-0.000222	-0.000590	RI	(OH)
-0.003119	-0.001239	-0.000687	RS	(OH)
-0.000696	-0.000570	-0.000562	LS	(nH)
-0.009661	-0.039311	-0.037724	CGS	(pF)
0.000179	-0.011340	-0.015465	CDG	(pF)
0.000862	0.001608	0.003444	CDS	(pF)
0.022233	0.016452	0.006713	G	(/OH)
-0.002111	-0.001573	-0.001323	T	(ps)

COMD>
 Input : SAVE ALL3L1
COMD>
 Input : READ ALLTHREE
    Reading circuit file...

    Working file: ALLTHREE.DAT
    Number of circuits: 3
    Measurement files: C85029A.DAT   C85029B.DAT   C85029C.DAT
COMD>
 Input : SAVE TEST1
COMD>
 Input : ED TEST1.DAT
        V A X   E D T   E D I T O R

```
COMD>
 Input : TYPE TEST1.DAT

*All three measurements C85029A, C85029B and C85029C
BLK
*        common variables
         RO:2.E-6
         FO: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=FO T=TAU GGS=RO 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=FO T=TAU GGS=RO 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=FO T=TAU GGS=RO 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>
 Input : READ TEST1
      Reading circuit file...

    Working file: TEST1.DAT
    Number of circuits: 3
    Measurement files: C85029A.DAT    C85029B.DAT    C85029C.DAT
COMD>
 Input : L1

    Working file: TEST1.DAT
    Number of circuits: 3
    Measurement files: C85029A.DAT    C85029B.DAT    C85029C.DAT

      Start modelling ...
      You can press any key to interrupt optimization

        Iteration  1      L1 error    2.6936188
        Iteration  2      L1 error    2.1329496
        Iteration  3      L1 error    1.4297490
        Iteration  4      L1 error    0.7262558
        Iteration  5      L1 error    0.8383650
        Iteration  6      L1 error    0.5615602
        Iteration  7      L1 error    0.5619905
        Iteration  8      L1 error    0.5394992
        Iteration  9      L1 error    0.5268831
        Iteration 10      L1 error    0.5189538
        Iteration 11      L1 error    0.5184772
        Iteration 12      L1 error    0.5115020
        Iteration 13      L1 error    0.5112324
        Iteration 14      L1 error    0.5111505
        Iteration 15      L1 error    0.5111022
        Iteration 16      L1 error    0.5110850
        Iteration 17      L1 error    0.5109553
```

```
        Optimization Completed
         17 iterations      22.30 CPU seconds
           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)
      0.0070    0.0050      0.0070    0.0059      0.0070    0.0059   GDS(/OH)
      1.0000    0.0569      1.0000    0.3402      1.0000    0.5920   RI  (OH)
      1.0000    0.9679      1.0000    0.4930      1.0000    0.0376   RS  (OH)
      0.0200    0.0046      0.0200    0.0046      0.0200    0.0046   LS  (nH)
      1.4000    0.6563      1.4000    0.4057      1.4000    0.3190   CGS (pF)
      0.0700    0.0296      0.0700    0.0492      0.0700    0.0620   CDG (pF)
      0.0400    0.2218      0.0400    0.2168      0.0400    0.2072   CDS (pF)
      0.0900    0.0633      0.0900    0.0497      0.0900    0.0394   G   (/OH)
      7.0000    4.2061      7.0000    4.2061      7.0000    4.2061   T   (ps)

COMD>
 Input : SAVE TEST1L1
COMD>
 Input : READ ALLTHREE
      Reading circuit file...

      Working file: ALLTHREE.DAT
      Number of circuits: 3
      Measurement files: C85029A.DAT   C85029B.DAT   C85029C.DAT
COMD>
 Input : SAVE TEST2
COMD>
 Input : ED TEST2.DAT
         V A X    E D T    E D I T O R

COMD>
 Input : TYPE TEST2.DAT

*All three measurements C85029A, C85029B and C85029C
BLK
*        common variables
         RO:2.E-6
         FO:1.E3GHZ
         RGM:? 1.00000?
         LS:? 0.1000NH?
         RDD:? 1.00000?
         TAU:? 0.01000NS?
*        variable for the first circuit
         G1:? 0.1000?
         C1:? 1.0000PF?
         C2:? 1.0000PF?
         C3:? 1.000PF?
         R1:? 1.00000?
         R2:? 1.00000?
         GG3:? 0.0100?
*        variable for the second circuit
         G2:? 0.1000?
         C4:? 1.0000PF?
```

```
            C5:? 1.0000PF?
            C6:? 1.0000PF?
            R4:? 1.00000?
            R5:? 1.00000?
            GG6:? 0.0100?
*           variable for the third circuit
            G3:? 0.10000?
            C7:? 1.0000PF?
            C8:? 1.0000PF?
            C9:? 1.0000PF?
            R7:? 1.00000?
            R8:? 1.00000?
            GG9:? 0.01000?
*
FET 1 2 G=G1 CGS=C1 F=FO T=TAU GGS=RO 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=FO T=TAU GGS=RO 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=FO T=TAU GGS=RO 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 1.0GHZ
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>
 Input : READ TEST2
     Reading circuit file...

    Working file: TEST2.DAT
    Number of circuits: 3
    Measurement files: C85029A.DAT   C85029B.DAT   C85029C.DAT
```

COMD>
Input : L1

    Working file: TEST2.DAT
    Number of circuits: 3
    Measurement files: C85029A.DAT   C85029B.DAT   C85029C.DAT

    Start modelling ...
    You can press any key to interrupt optimization

        Iteration 1   L1 error   6.6676922
        Iteration 2   L1 error   5.6123438
        Iteration 3   L1 error   4.2343659
        Iteration 4   L1 error   3.0937769
        Iteration 5   L1 error   1.6524744
        Iteration 6   L1 error   1.1513814
        Iteration 7   L1 error   0.6289817
        Iteration 8   L1 error   0.8143499
        Iteration 9   L1 error   0.5297607
        Iteration 10   L1 error   0.5004176
        Iteration 11   L1 error   0.5031931
        Iteration 12   L1 error   0.4981698
        Iteration 13   L1 error   0.4984140
        Iteration 14   L1 error   0.4979580
        Iteration 15   L1 error   0.4980265
        Iteration 16   L1 error   0.4979212

    Optimization Completed
      16 iterations   42.72 CPU seconds
        FET MODEL PARAMETERS

FETMDL1		FETMDL2		FETMDL3			
starting	solution	starting	solution	starting	solution		
1.0000	2.2309	1.0000	2.2309	1.0000	2.2309	RG	(OH)
1.0000	3.7900	1.0000	3.7900	1.0000	3.7900	RD	(OH)
0.0100	0.0050	0.0100	0.0061	0.0100	0.0061	GDS	(/OH)
1.0000	0.3836	1.0000	0.5950	1.0000	0.9664	RI	(OH)
1.0000	0.9584	1.0000	0.8376	1.0000	0.5247	RS	(OH)
0.1000	0.0039	0.1000	0.0039	0.1000	0.0039	LS	(nH)
1.0000	0.7191	1.0000	0.4394	1.0000	0.3434	CGS	(pF)
1.0000	0.0308	1.0000	0.0478	1.0000	0.0612	CDG	(pF)
1.0000	0.2226	1.0000	0.2226	1.0000	0.2145	CDS	(pF)
0.1000	0.0696	0.1000	0.0518	0.1000	0.0408	G	(/OH)
10.0000	3.9480	10.0000	3.9480	10.0000	3.9480	T	(ps)

COMD>
Input : SAVE TEST2L1
COMD>
Input : 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.

GRAPHICS GENERATED BY FETSCG

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.

MEASUREMENT: C85029A.DAT

MODEL: FETMDL1

MS22   AS22

MS12   AS12

MS21   AS21

MS11   AS11
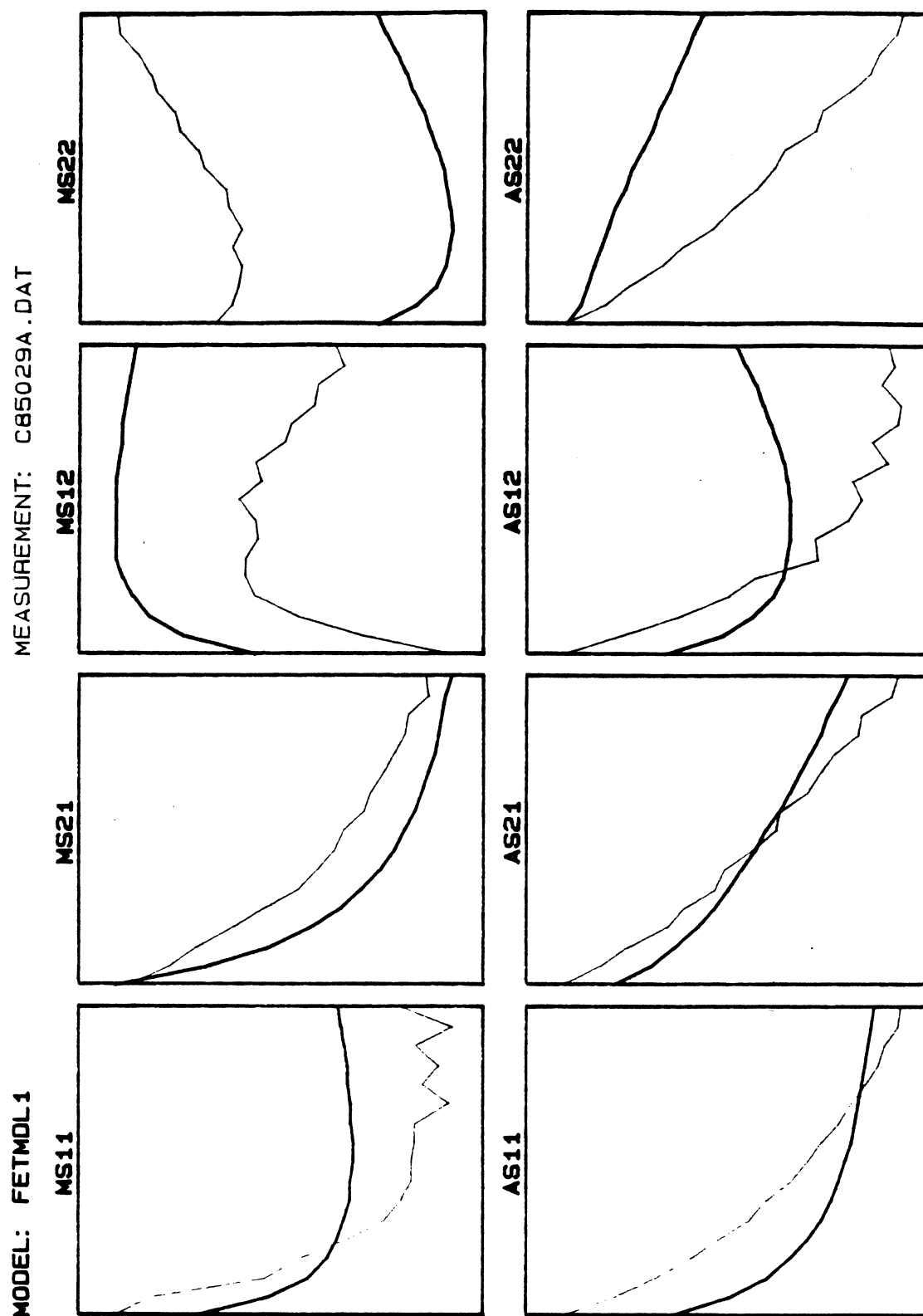
Fig. 1   Measured and modelled responses for C85029A.
Starting point.
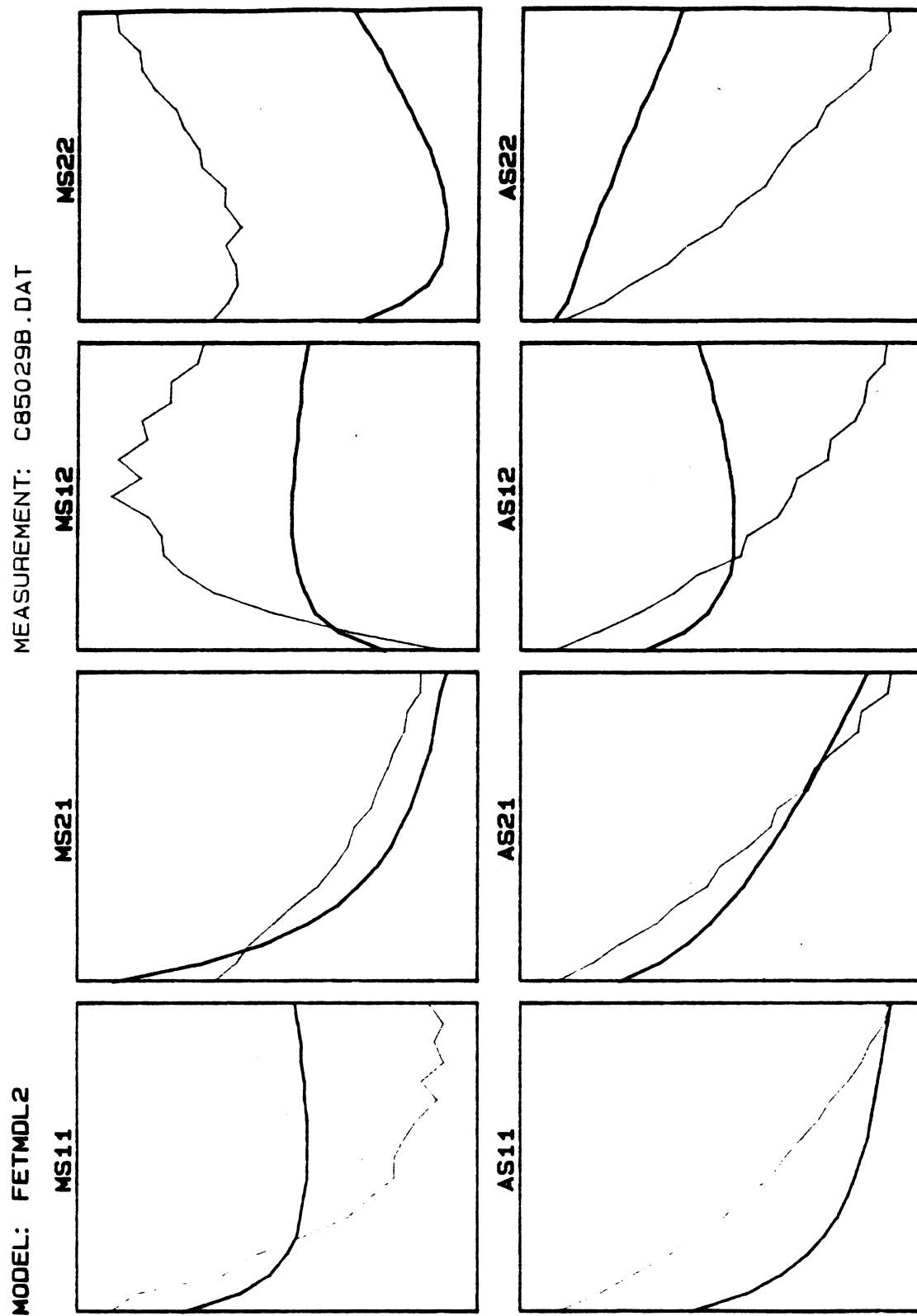
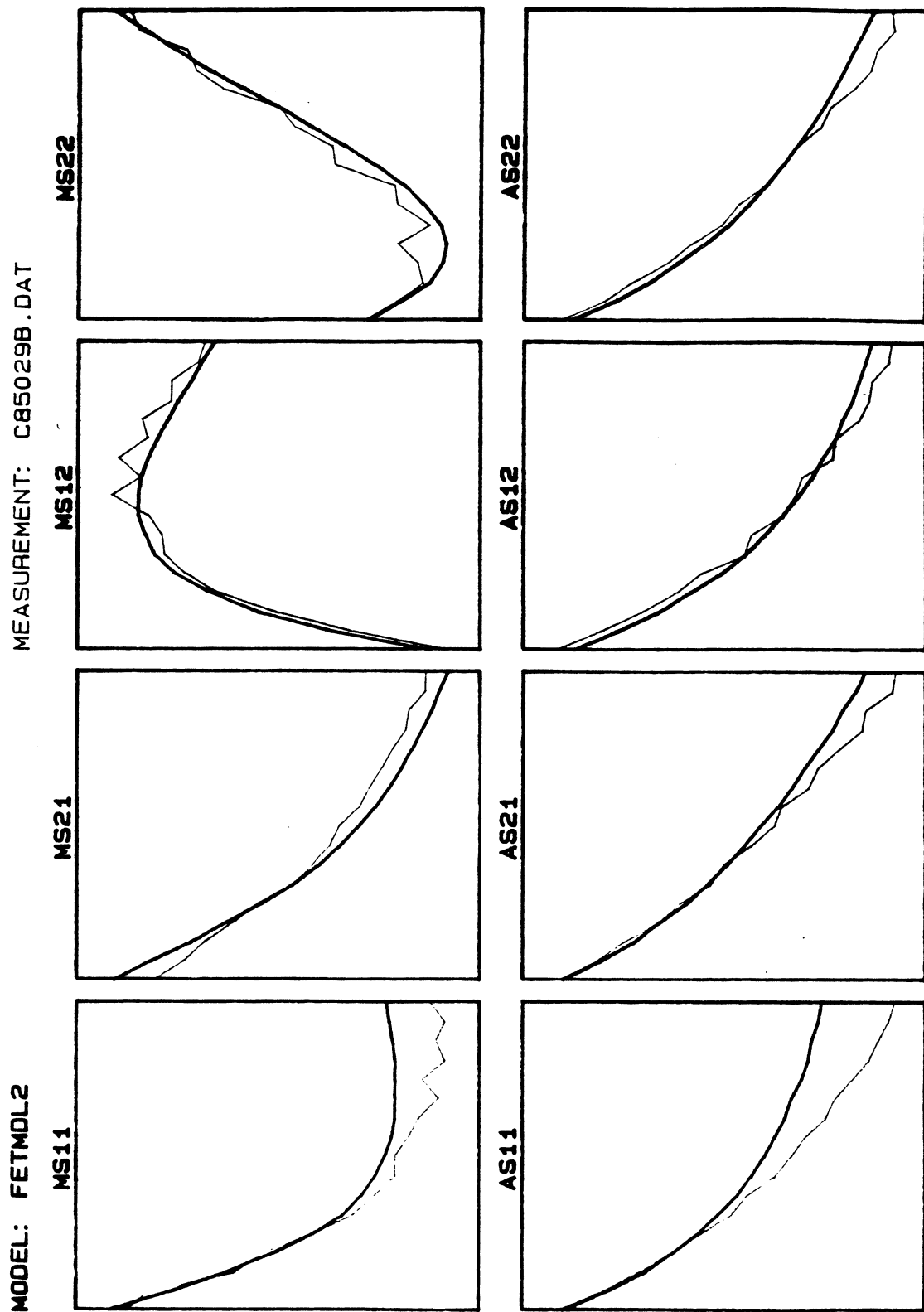Fig. 2   Measured and   modelled   responses for C85029B.
         Starting point.

MEASUREMENT: C85029C.DAT

MODEL: FETMDL3

MS22

AS22

MS12

AS12

MS21

AS21

MS11

AS11
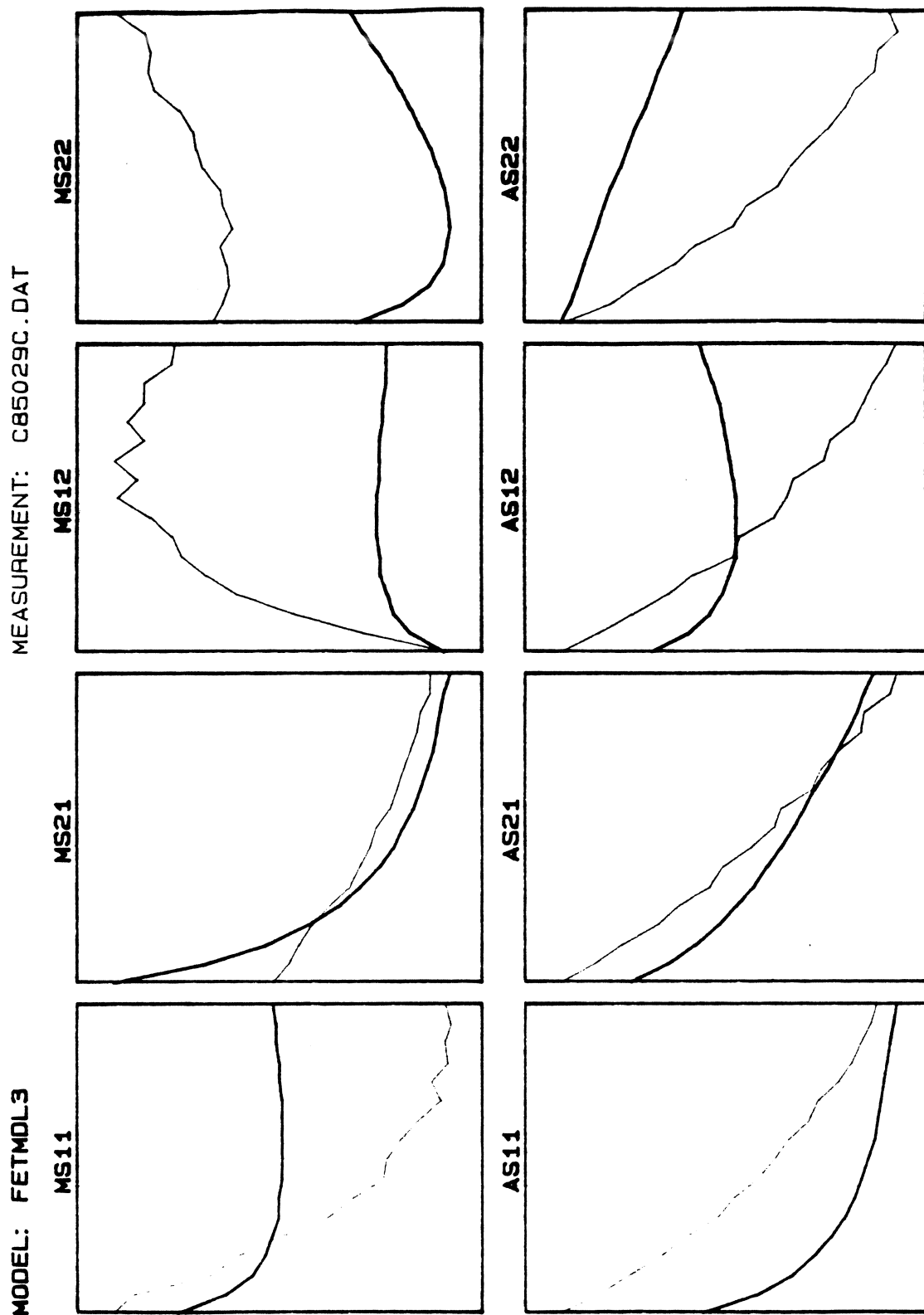
Fig. 3 Measured and modelled responses for C85029C.
Starting point.

MEASUREMENT: C85029A.DAT

MODEL: FETMDL1

MS22

AS22
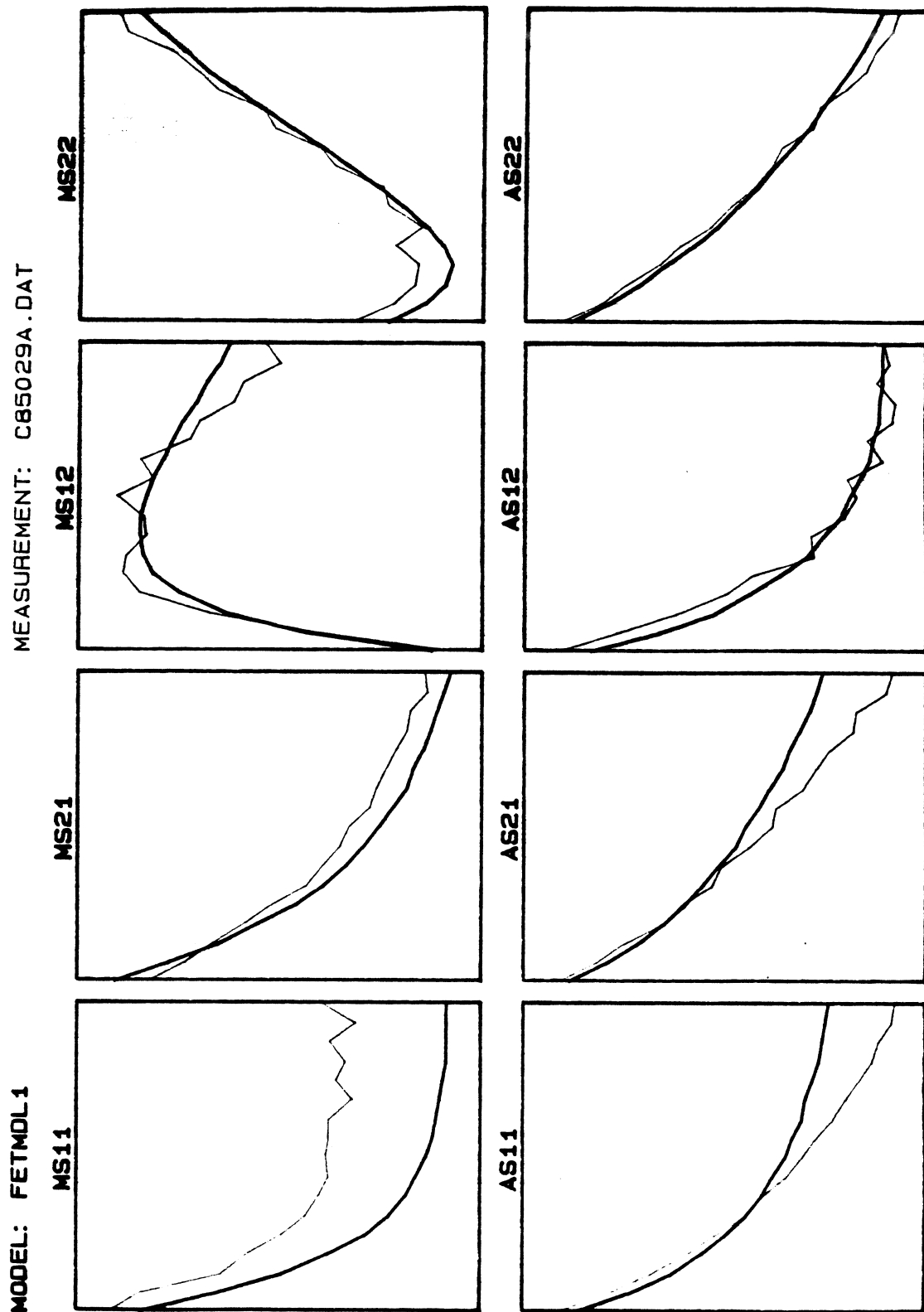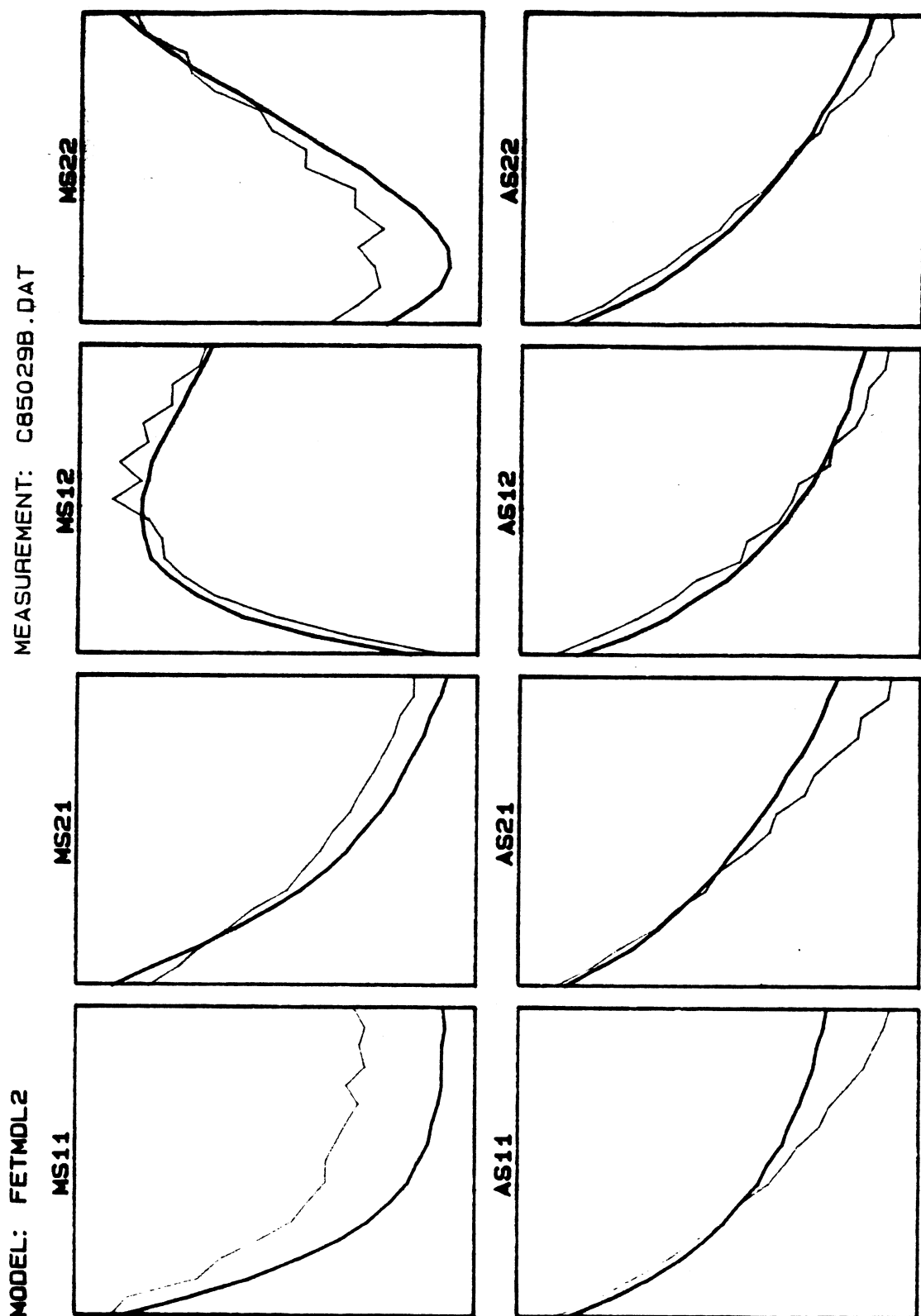
MS12

AS12

MS21

AS21

MS11

AS11
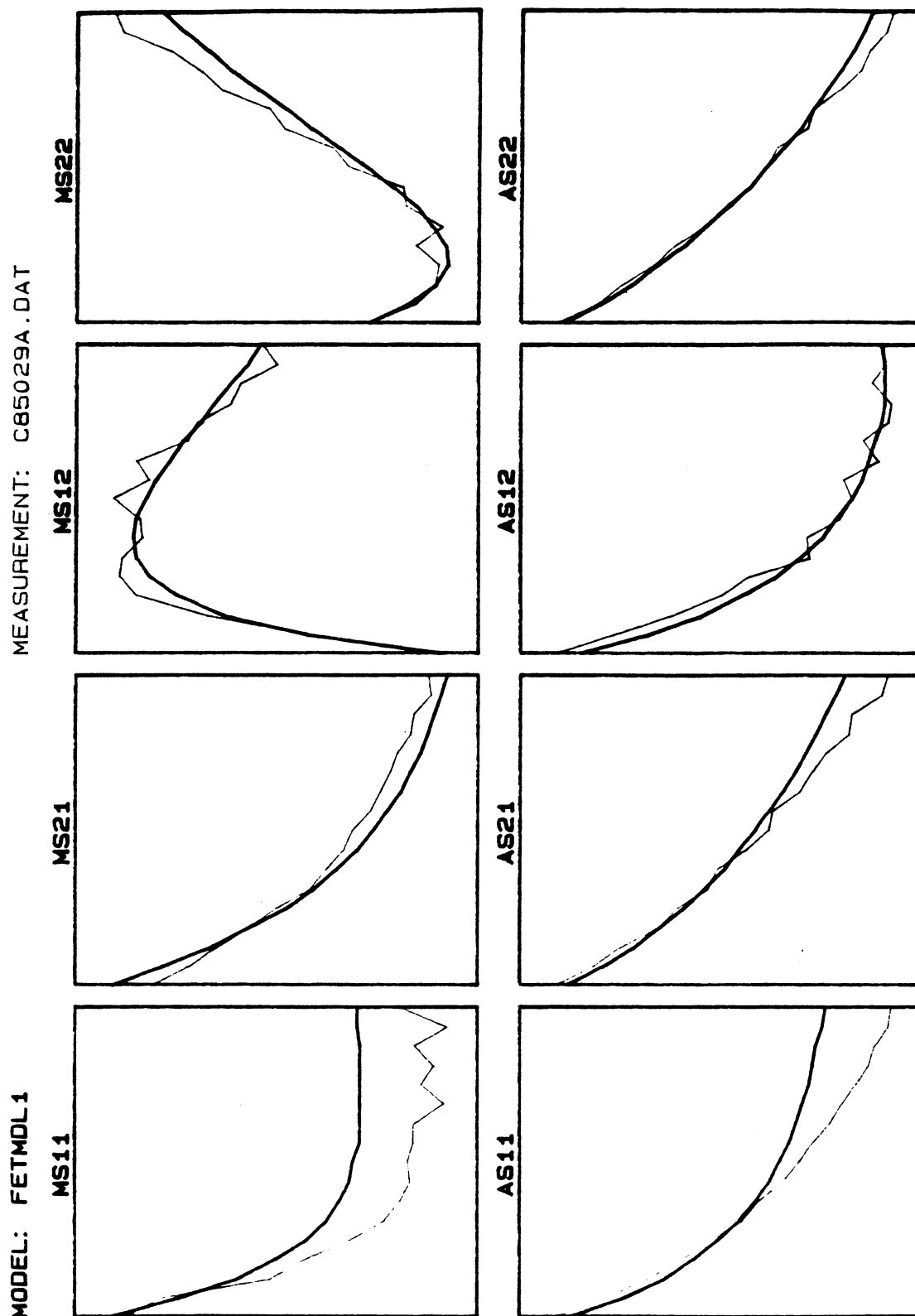
Fig. 4 Measured and modelled responses for C85029A.
Simultaneous L_1 optimization is used.

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

MEASUREMENT: C85029C.DAT

MODEL: FETMDL3

MS22   MS12   MS21   MS11

AS22   AS12   AS21   AS11
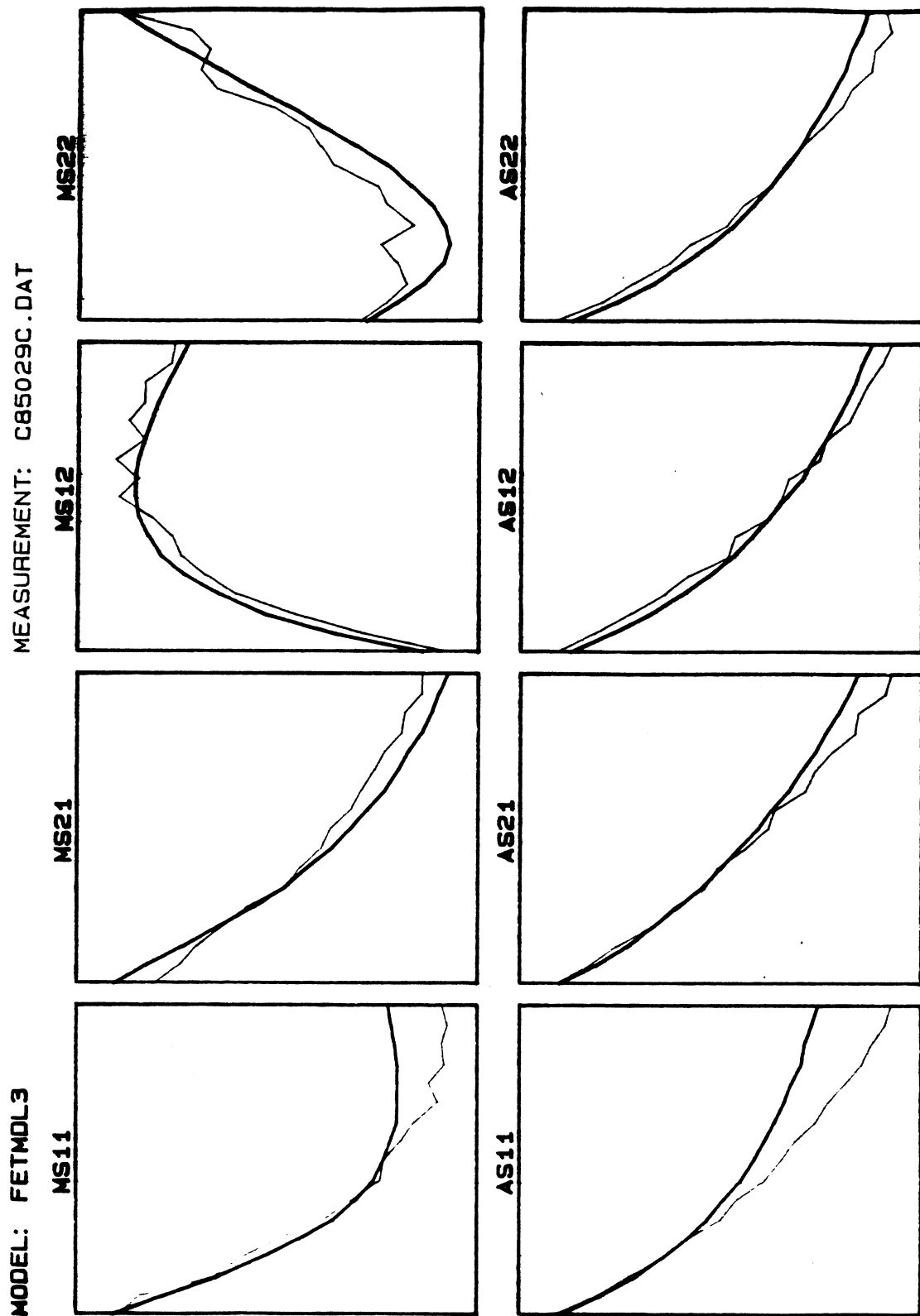
Fig. 6   Measured and   modelled   responses   for C85029C.
Simultaneous L_1 optimization   is   used.

MEASUREMENT: C85029A.DAT

MODEL: FETMDL1

MS22   MS12   MS21   MS11

AS22   AS12   AS21   AS11

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

MEASUREMENT: C85029B.DAT

MODEL: FETMDL2

MS22

MS12

MS21

MS11

AS22

AS12

AS21

AS11

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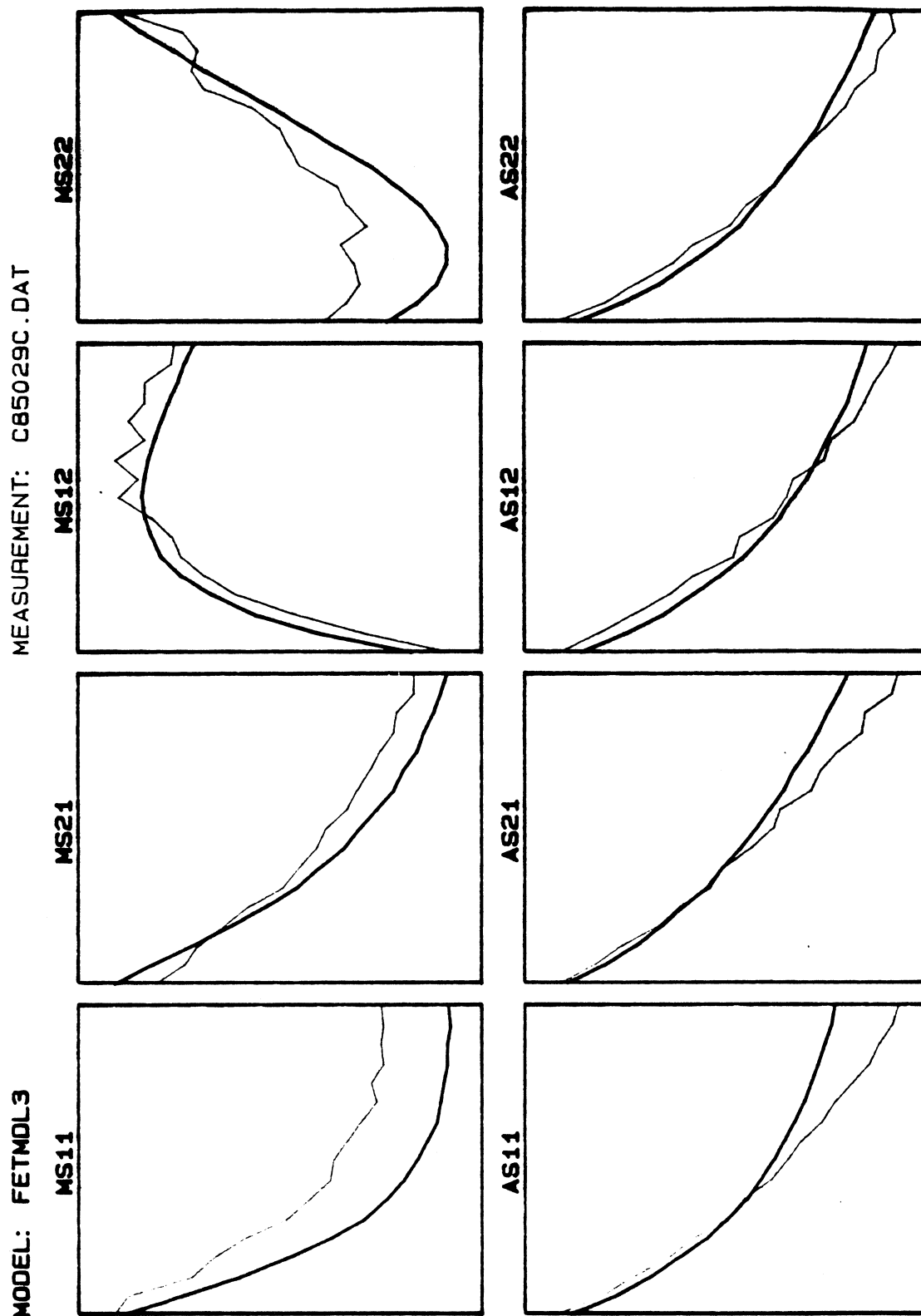Simultaneous L_2 optimization is used.

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

COMPARISON OF RESULTS BETWEEN FETSC AND COMPACT

The performance of FETSC is compared with COMPACT in order to establish any advantages FETSC may have over a popular and commercially available software system. Table I summarizes the results obtained using FETSC in the interactive session examples which describe the use of the package. All the results in Table I were obtained by performing two optimizations, each involving three circuits (simultaneous processing of three measurement files C85029A.DAT, C85029B.DAT and C85029C.DAT). The first optimization identified by letter A in the table corresponds to the file ALLTHREE.DAT and the second optimization (B in the table) corresponds to the file TEST2.DAT (different starting values) in the interactive session which describes a multi-circuit example.

Using data files compatible with COMPACT, such as the one shown on the next page (starting values identified as A), 6 optimizations were performed to obtain the results illustrated in Table II. Starting values for cases A and B are the same as the ones used with FETSC. In most cases the optimization is terminated after 30 iterations since the decrease in the objective function between successive iterations becomes negligible.

A careful examination of Tables I and II reveals that for all parameters except RI, the results obtained using FETSC with two different sets of starting values are more consistent with each other than the results obtained using COMPACT. The match between measured and modelled responses in all cases are excellent for both programs and the results for one program cannnot be preferred to the other from the point of view of responses.

The total CPU time for obtaining the results of Table II is

in excess of 1000 seconds on a Cyber 170/730 computer, whereas on a VAX 8600 the results of Table I were obtained in about 85 seconds.

The following is an appropriate data file for COMPACT.

```
* MEASUREMENTS IN THIS FILE ARE FROM C85029A.S2P
*
* RGM,RI,RS,RDD
*
RES AA SE -1
RES BB SE -1
RES CC SE -1
RES DD SE -1
*
* CSG,CGD,CSD
*
CAP EE SE -1.4
CAP FF SE -.07
CAP GG SE -.4
*
* SOURCE-LEAD VIA SOURCE INDUCTANCE
*
IND HH SE -.2E-01
*
* GENERATOR
*
GEN II VC 5.0E5 -143 -90.0 1.0E12 -.7E-5
*
* CONNECT ALL ELEMENTS TOGETHER
*
CON AA T2 1 3
CON EE T2 3 4
CON BB T2 4 5
CON II T4 3 4 5 6
CON FF T2 3 6
CON CC T2 5 8
CON HH T2 8 0
CON GG T2 6 5
CON DD T2 6 2
DEF AA T2 1 2
TWO BB S1 50
SET AA BB
PRI AA S1 50
END
2000 18000 1000
END
```

.9546	−46.72	4.0405	145.54	.0291	62.95	.6010	−21.43
.9392	−66.98	3.6149	129.27	.0388	52.47	.5808	−32.82
.8944	−83.24	3.3323	118.50	.0458	42.58	.5718	−39.93
.8789	−97.95	2.9539	102.85	.0507	33.91	.5701	−48.94
.8598	−108.88	2.6428	95.28	.0518	28.76	.5808	−54.82
.8460	−120.97	2.2946	82.85	.0517	18.44	.5683	−63.42
.8388	−127.78	2.0989	78.94	.0503	18.99	.5845	−68.54
.8340	−137.66	1.9225	67.49	.0505	12.84	.5867	−75.58
.8350	−143.32	1.7984	58.95	.0525	10.51	.6089	−79.69
.8326	−149.51	1.5910	56.35	.0499	12.37	.6166	−83.21
.8326	−155.26	1.5106	46.49	.0507	6.11	.6360	−91.66
.8196	−161.01	1.3838	40.82	.0473	8.76	.6427	−93.39
.8301	−166.19	1.2945	34.54	.0466	4.40	.6633	−101.10
.8242	−172.00	1.1615	24.82	.0442	3.98	.6718	−106.42
.8332	−174.63	1.1335	23.98	.0436	7.27	.6845	−108.67
.8190	−179.96	.9365	11.88	.0408	5.08	.7045	−113.75
.8394	−180.64	.9688	8.12	.0420	6.08	.7098	−115.22

END
0.01
1 1 1 1
END

TABLE I

RESULTS OBTAINED USING FETSC

Parameter	C85029A		C85029B		C85029C	
	A	B	A	B	A	B
RG	2.5487	2.2309	2.5487	2.2309	2.5487	2.2309
RD	3.7457	3.7900	3.7457	3.7900	3.74657	3.7900
GDS	0.0050	0.0050	0.0061	0.0061	0.0061	0.0061
RI	0.0000	0.3836	0.1715	0.5950	0.4776	0.9664
RS	1.0042	0.9584	0.9077	0.8376	0.6243	0.5247
LS	0.0039	0.0039	0.0039	0.0039	0.0039	0.0039
CGS	0.7224	0.7191	0.4414	0.4394	0.3451	0.3434
CDG	0.0306	0.0308	0.0476	0.0478	0.0610	0.0612
CDS	0.2227	0.2226	0.2227	0.2226	0.2148	0.2145
G	0.0698	0.0696	0.0520	0.0518	0.0409	0.0408
T	3.9600	3.9480	3.9600	3.9480	3.9600	3.9480

TABLE II

RESULTS OBTAINED USING COMPACT

Parameter	C85029A		C85029B		C85029C	
	A	B	A	B	A	B
RG	1.9446	1.6456	1.8780	2.0264	2.1496	2.1408
RD	0.9547	1.3896	0.8983	1.4926	0.9147	1.0759
GDS	0.0052	0.0052	0.0064	0.0064	0.0065	0.0066
RI	1.4737	1.0605	1.3875	1.1544	1.4306	1.0460
RS	0.8177	0.8417	0.8694	0.9231	0.7467	0.8622
LS	0.0043	0.0051	0.0009	0.0019	0.0017	0.0015
CGS	0.7435	0.7337	0.5125	0.5078	0.4086	0.4136
CDG	0.0319	0.0326	0.0477	0.0483	0.0610	0.0603
CDS	0.2161	0.2200	0.2139	0.2159	0.2057	0.2073
G	0.0748	0.0741	0.0568	0.0572	0.0447	0.0449
T	6.2024	6.2175	5.2949	5.1263	5.1862	5.1289
L2 objective	0.0899	0.0898	0.0857	0.0861	0.0846	0.0843
# of iterations	28	40	30	30	30	30

QUICK REFERENCE FOR DIFFERENT VERSIONS

FETSC: VAX Version

Purpose: small-signal modelling of FET devices based on S-parameter measurements

Features: SUPERCOMPACT file compatibility

Simultaneous processing of up to 3 sets of measurements

Gradient-based L1 and L2 optimizations

Operating System: VAX VMS

Object Modules: FETSC.OBJ --- main program; user interface;

SCFILE.OBJ -- SUPERCOMPACT file interpretor;

FETFDF.OBJ -- FET model simulation;

L1ABC.OBJ --- L1 optimizer;

QUASI.OBJ --- Quasi-Newton optimizer.

Linking: $LINK FETSC+SCFILE+FETFDF+L1ABC+QUASI

Executable File: FETSC.EXE

Auxiliary File: FETSC.MSG --- error messages.

FETSCG: IBM/AT Version

Purpose: small-signal modelling of FET devices based on S-parameter
measurements

Features: SUPERCOMPACT file compatibility

Simultaneous processing of up to 3 sets of measurements

Gradient-based L1 and L2 optimizations

Color graphics

Operating System: IBM PC-DOS V3.10

Hardware Requirements: 512K RAM, EGA, Color Monitor, 8087 Coprocessor

Fortran Compiler: MS-FORTRAN V3.3 Compiler, Linker, Libraries

Object Modules: FETSCG.OBJ --- main program; user interface;

SCFILE.OBJ -- SUPERCOMPACT file interpretor;

FETFDFG.OBJ -- FET model simulation;

L1ABC.OBJ --- L1 optimizer;

QUASI2.OBJ --- Quasi-Newton optimizer;

FETPLT.OBJ --- Graphics plotting routine;

Libraries: FORTRAN.LIB   (MS-FORTRAN V3.3)

MATH.LIB   (rename MS-FORTRAN V3.3 8087.LIB)

CEXEC.LIB   (MS-FORTRAN V3.3 C-language interface)

IBMTXT.LIB   (text screen utility for IBM/AT)

IBMGRF.LIB   (graphics utility for IBM/AT)

Linking: $LINK FETSCG+SCFILE+FETFDFG+L1ABC+
          QUASI2,,NUL,IBMTXT+IBMGRF+CEXEC

Executable File: FETSCG.EXE

Auxiliary File: FETSCG.MSG --- error messages;

CED.EXE ------ full screen editor.