Description of an Interface Between MSC/NASTRAN and the $MATRIX_X$ Control Design Program

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1 Abstract

This paper describes an existing interface which allows extraction of linear models from an MSC/NASTRAN output file and conversion into $MATRIX_X$ readable format for control design and simulation. The interface is demonstrated using an MSC/NASTRAN model of a satellite microwave antenna.

In addition to the existing interface, a proposed expanded interface allowing additional information to be transfered from MSC/NASTRAN to $MATRIX_X$ is presented. Candidate information includes component mass and stiffness matrices, and outputs from MSC/NASTRAN's Design Sensitivity Analysis (DSA) package. This sensitivity data would allow open or closed loop robustness analysis, and simultaneous structural and controller design.

2 Introduction

On most projects involving the design of a controlled structure the structural design and controller design are performed sequentially. It can often be a cumbersome task to translate the structural analysis results into a form that can be easily utilized for controller design. Frequently the information is manually extracted from MSC/NASTRAN output files or a custom program is written. Such an approach can induce errors into the model, and can also be quite time comsuming, especially when frequent redesigns are performed. In order to overcome these problems, Integrated Systems Inc., has developed an interface to MSC/NASTRAN that allows a control engineer to detail the type and location of sensors and actuators on the structure, as well as the modes of interest, and have a state space model extracted from the MSC/NASTRAN output file. The state space system is given in a format

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that can be loaded directly into MATRIX_X where control design and simulation can be performed.

Other than system level design considerations such as incorporating the sensors and actuators for the controller into the structure, there is usually very little influence of the controller design on the structural design. However, for the controller and structure to interact efficiently the two should be designed simultaneously. Some results of a simple truss where the controller and structure were designed separately and then together are presented, [3], showing a significant increase in performance in the latter case. This type of design can be practically achieved with a somewhat higher level interface than the existing one described above. Such an interface would allow not only the nominal dynamics, but component mass and stiffness matrices to be passed from MSC/NASTRAN to MATRIX_X. These could then be used with the general optimization package in MATRIX_X to generate a closed loop optimal structure.

For large systems, i.e. 1000 degrees of freedom, it is cumbersome to work with the full order model. In this case the structure can still be optimized in closed loop if a subset of the eigenvectors is transfered to MATRIX_X, along with their sensitivities to the design parameters. MSC/NASTRAN's DSA package generates the required sensitivities, which could then be passed to MATRIX_X using an extended interface.

3 The Existing Interface

The existing interface allows easy transfer of the modal analysis data from the MSC/NASTRAN finite element program to the MATRIX_X control system design and analysis program.

The inputs to the MSC/NASTRAN - MATRIX_X Interface are:

- Modal data generated by MSC/NASTRAN.
- An ASCII text file, whose contents are summarized in Figure 1. The contents of this file dictate the modal analysis results which are extracted from MSC/NASTRAN for use in MATRIX_X.

For analysis of the control system model in MATRIX_X, the state equation is of the form

$$\dot{x} = Ax + Bu \tag{3.1}$$

and the output equation is of the form

$$y = Cx + Du \tag{3.2}$$

where A and B are matrices which relate the state and input to the state derivative.

In MSC/NASTRAN [5] the second order linear dynamical system is represented as

$$
\begin{aligned}
M\ddot{q} + Kq &= Gu \\
y &= Hq,
\end{aligned}
$$

where

$$
\begin{aligned}
M &= \text{symmetric positive mass matrix} \\
K &= \text{symmetric non-negative stiffness matrix} \\
G &= \text{control influence matrix} \\
H &= \text{measurement matrix} \\
q &= \text{nodal displacements} \\
u &= \text{system inputs} \\
y &= \text{system outputs}
\end{aligned}
$$

The system eigensolution takes the form

$$(M\omega_i^2 - K)\phi_i = 0$$

and the eigenvector matrix, $\Phi = [\phi_1 ... \phi_n]$, can be used to transform to modal coordinates.

$$\Phi^T M \Phi \ddot{\eta} + \Phi^T K \Phi \eta = \Phi^T G u \tag{3.3}$$

$$y = H\Phi\eta \tag{3.4}$$

It is assumed that the matrix Φ has been normalized such that

$$\Phi^T M \Phi = I \tag{3.5}$$

$$\Phi^T K \Phi = \begin{bmatrix} \omega_1^2 & & \\ & \ddots & \\ & & \omega_n^2 \end{bmatrix} = \Omega^2 \tag{3.6}$$

No damping information is extracted from MSC/NASTRAN, in lieu of this the user must specify the modal damping to be used. This is done by specifying a single damping ratio in the mode/node selection file, which is used for all modes. If a different form of damping is desired, the system can easily be altered to incorporate it once the system is in MATRIX_X.

Substituting equations 3.5 and 3.6 into 3.3 and introducing the modal damping yields

$$\ddot{\eta} + \begin{bmatrix} 2\zeta\omega_1 & & \\ & \ddots & \\ & & 2\zeta\omega_n \end{bmatrix} \dot{\eta} + \begin{bmatrix} \omega_1^2 & & \\ & \ddots & \\ & & \omega_n^2 \end{bmatrix} \eta = \Phi^T G u \tag{3.7}$$

Equation 3.7 can be rewritten as

$$\ddot{\eta} = \begin{bmatrix} -\omega_1^2 & & \\ & \ddots & \\ & & -\omega_n^2 \end{bmatrix} \eta + \begin{bmatrix} -2\zeta\omega_1 & & \\ & \ddots & \\ & & -2\zeta\omega_n \end{bmatrix} \dot{\eta} + \Phi^T G u \tag{3.8}$$

This second order matrix differential equation can be converted to a first order matrix differential equation as shown below.

$$\begin{bmatrix} \dot{\eta} \\ \ddot{\eta} \end{bmatrix} = \begin{bmatrix} 0 & & & 1 & & \\ & \ddots & & & \ddots & \\ & & 0 & & & 1 \\ -\omega_1^2 & & & -2\zeta\omega_1 & & \\ & \ddots & & & \ddots & \\ & & -\omega_n^2 & & & -2\zeta\omega_n \end{bmatrix} \begin{bmatrix} \eta \\ \dot{\eta} \end{bmatrix} + \begin{bmatrix} 0 \\ \Phi^T G \end{bmatrix} u \tag{3.9}$$

This is a state-space system of the desired form given in equation 3.1, with the state vector x defined as

$$x = \begin{bmatrix} \eta \\ \dot{\eta} \end{bmatrix}$$

Also in equation 3.9 the dynamics matrix A premultiplies x and the input matrix B premultiplies u.

The major reason for converting to a first order differential equation is that nearly all modern control design methods are based on dealing with systems of this form. Therefore, the interface not only extracts the required information from the MSC/NASTRAN output file, but puts it into a form that the control engineer is used to dealing with.

In equation 3.9 the system eigenvalues only affect the A matrix, which specifies the dynamic characteristics of the system such as bandwidth, and the eigenvectors affect only the B matrix, or the mapping of the input forces and torques (commands and disturbances) to the system.

So far we have only dealt with positions as outputs in equations 3.2 and 3.4, but we can easily add velocities and accelerations by differentiating equation 3.4, which gives.

$$\dot{y}_v = H\Phi\dot{\eta} \tag{3.10}$$
$$\ddot{y}_a = H\Phi\ddot{\eta} \tag{3.11}$$

These can be combined with 3.4 to form a new output equation. Additionally, equation 3.8 has been substituted for $\ddot{\eta}$ in equation 3.11.

$$y = \begin{bmatrix} H_p\Phi & 0 \\ 0 & H_v\Phi \\ -H_a\Phi\Omega^2 & -2H_a\Phi\zeta\Omega \end{bmatrix} \begin{bmatrix} \eta \\ \dot{\eta} \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ H_a\Phi\Phi^T G \end{bmatrix} u \qquad (3.12)$$

The subscripts p, v and a denote (translational or rotational) displacement, velocity and acceleration respectively. Equation 3.12 is of the same form as equation 3.2, with the output matrix C premultiplying the state vector x, and the direct terms matrix D premultiplying the input vector u.

The dimensions of the state space system submatrices are:

Matrix	Row Dimension	Column Dimension
A	# modes	# modes
B	# modes	# inputs
C	# outputs	# modes
D	# outputs	# inputs

The inputs to the state space system are actuator or disturbance forces and torques in nodal coordinates. The outputs are displacements, velocities and accelerations in nodal coordinates.

4 The Mode/Node Selection File

Prior to execution of the interface program which extracts the modal analysis data from the MSC/NASTRAN output file, the user must create the Mode/Node selection file. This file specifies the modes to be selected, as well as the sensor and actuator types and nodal locations. This input file can be created with any text editor in the format shown in Figure 1. Entries on each line must be separated by either a comma or a blank space.

The terms in Figure 1 are as described in the following paragraphs. The control system model (in $\mathrm{MATRIX_X}$) typically consists of:

- Actuators and Disturbances : These correspond to the *inputs* in the MSC/-NASTRAN mode/node selection file. These inputs are at node points which correspond to locations where the actuators or external disturbances are exerting a force or torque on a finite element.

- Sensors : These correspond to the *outputs* in the MSC/NASTRAN mode/node selection file. These outputs are points in the finite element model where the position, velocity or acceleration are measured. They can be actual sensors on the system, or just points of interest for analysis.

Number of Modes Selected (1 ≤ 200)

Selected Mode List (number of modes selected entries)

Zeta (Percentage of Critical Damping) (0.0 < 1.0)

Number of Inputs (1 ≤ Number of Nodes where an input is located)

Repeated number of input times {
- Number of nodes participating in this input — Output Type
- Node Number — Projection 6 : Entries (-1.0 ≤ 1.0)

}

Number of Outputs (1 ≤ Number of Nodes where an output is located)

Repeated number of output times {
- Number of nodes participating in this output — Output Type (1 ≤ 3)
- Node Number — Projection 6 : Entries (-1.0 ≤ 1.0)

}

Figure 1: MSC/NASTRAN Mode/Node Selection File Format

With these definitions, the entries in the MSC/NASTRAN mode/node selection file are enumerated below, with more detailed descriptions as required.

1. Number of modes to be extracted from the MSC/NASTRAN output file.

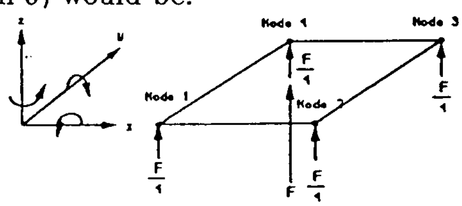
2. Enumerated list of the modes to be extracted

3. Percentage of critical damping (structural) used in the MSC/NASTRAN modal analysis.

4. Number of inputs (described above).

5. Number of inputs participating in this input. As an example, the projection of a force in the +z direction at the centroid of a finite element model quadrilateral element would be distributed to the four adjacent nodes. Therefore 4 nodes would participate, and the projection (See item 6) would be:

Node 1	0	0	0.25	0	0	0
Node 2	0	0	0.25	0	0	0
Node 3	0	0	0.25	0	0	0
Node 4	0	0	0.25	0	0	0



6. Projection. This is the component of the input or output to be extracted. Translation components along the x, y, z axes and rotation abouth the x, y, z

axes. For example, if the component to be extracted is a rotational component about the y axis, the projection would be `0 0 0 0 1 0`.

7. Number of outputs (described above)

8. Output type (measurement):

   (a) 1 - Position

   (b) 2 - Velocity

   (c) 3 - Acceleration

During execution of the MSC/NASTRAN data extraction program the user is prompted for the names of the two input files required by the program:

1. MSC/NASTRAN data file

2. Mode/Node selection file

The user is also prompted for the name of the output file which is generated. Any errors occuring during execution will terminate the program, after dispay of a detailed error message. The output file generated is in the proper format to be loaded directly into MATRIX_X.

5 Application Example of the Existing Interface

As a typical example, a MSC/NASTRAN model of a satellite microwave scanning antenna (courtesy of the Aerojet Corporation) was used. The model, as shown in Figure 2, consists of 1586 elements. The antenna had 50 modes below 500 Hz, which included 2 rigid body modes. For the control analysis it was deemed necessary to consider only the first 12 modes, all of which were below 200 Hz. The two rigid body modes were due to the fact that the motor and the antenna were free to rotate about the Y axis. The input to the MSC/NASTRAN data extraction program is shown in Figure 3. As can be seen, there are 12 modes requested from the MSC/NASTRAN output with 4 inputs and 12 outputs to be used for the MATRIX_X control model. These inputs and outputs are listed below

$$\text{inputs} = \begin{bmatrix} \text{bearing friction 1} \\ \text{bearing friction 2} \\ \text{main motor torque} \\ \text{momentum compensator motor torque} \end{bmatrix}$$

$$
\text{outputs} = \begin{bmatrix} \text{antenna center x displacement} \\ \text{antenna center y displacement} \\ \text{antenna center z displacement} \\ \text{antenna center y rotation} \\ \text{antenna tip x displacement} \\ \text{antenna tip y displacement} \\ \text{antenna tip z displacement} \\ \text{antenna tip y rotation} \\ \text{motor shaft encoder} \\ \text{momentum compensator motor rotation} \\ \text{motor shaft rate} \\ \text{momentum compensator motor rate} \end{bmatrix}
$$

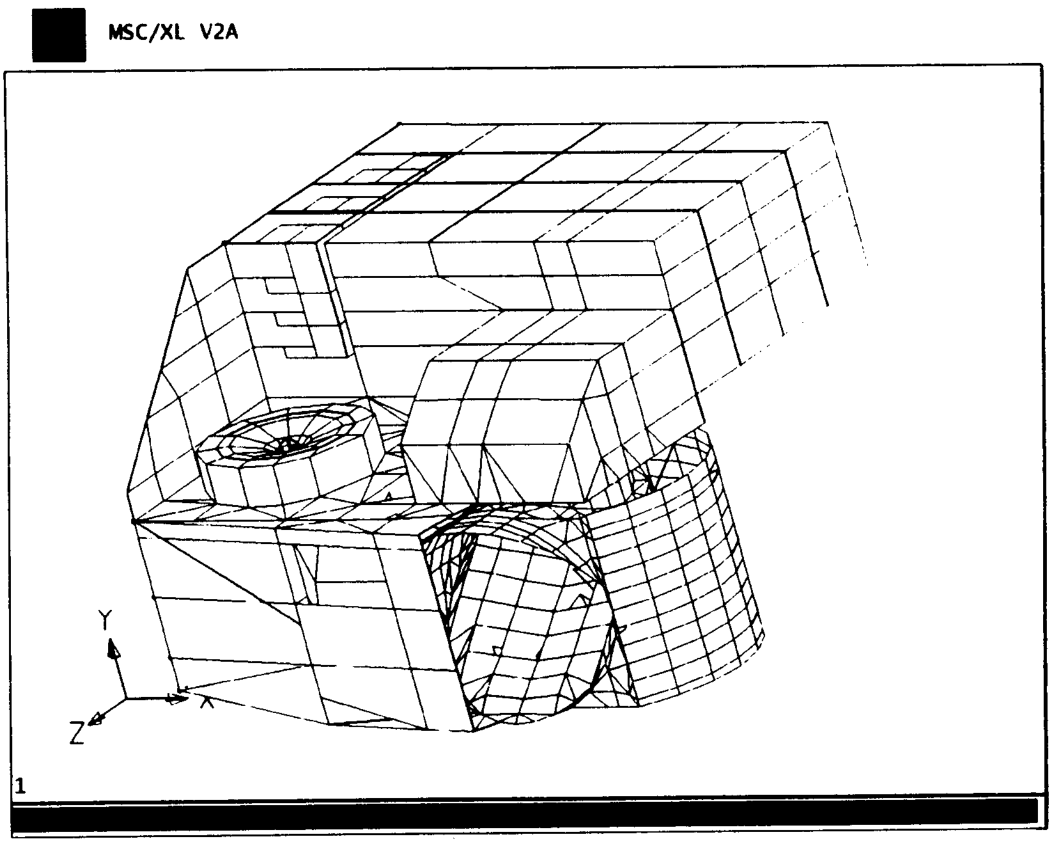


Figure 2: MSC/NASTRAN Model of a Satellite Scanning Antenna

The selection file on the next page describes the grid location of the control model inputs and outputs on the MSC/NASTRAN model. Of the 12 outputs only one is actually sensed on the system, namely the motor shaft encoder. All the others are just for verification of the controller and estimation of maximal antenna deformations.

```
! Selection file for a Microwave Scanning Antenna MSC/NASTRAN
! output data file.
!
12                               ! select 12 modes
1 2 3 4 5 6 7 8 9 10 11 12       ! mode numbers
0.001                            ! modal damping ratio for the modes
4                                ! number of inputs
1
1886 0 0 0 0 1 0                 ! first node for bearing friction
1
1887 0 0 0 0 1 0                 ! second node for bearing friction
1
1888 0 0 0 0 1 0                 ! motor torque
1
3108 0 0 0 0 1 0                 ! compensator motor torque
12                               ! number of outputs
1 1
1033 1 0 0 0 0 0                 ! antenna centre node x displacement
1 1
1033 0 1 0 0 0 0                 ! antenna centre node y displacement
1 1
1033 0 0 1 0 0 0                 ! antenna centre node z displacement
1 1
1033 0 0 0 0 1 0                 ! antenna centre node y rotation
1 1
1060 1 0 0 0 0 0                 ! antenna tip node x displacement
1 1
1060 0 1 0 0 0 0                 ! antenna tip node y displacement
1 1
1060 0 0 1 0 0 0                 ! antenna tip node z displacement
1 1
1060 0 0 0 0 1 0                 ! antenna tip node y rotation
1 1
1890 0 0 0 0 1 0                 ! motor shaft encoder rotation
1 1
3108 0 0 0 0 1 0                 ! compensator motor rotation
1 2
1890 0 0 0 0 1 0                 ! motor shaft rate
1 2
3108 0 0 0 0 1 0                 ! compensator motor rate
```

Figure 3: Example Input File

The linear state space system generated using this selection file was loaded into MATRIX_X for analysis. An example frequency response from the motor torque (input 3) to the motor shaft encoder (output 9) is shown in Figure 4. This result was obtained with just a few simple commands, as shown below.

```
<> LOAD 'FILE.DAT'
<> S=[A B(:,3) ; C(9,:) D(9,3)];
<> [OMEGA,DB,PHASE]=BODE(S,24,10*2*PI,1000*2*PI,300);
```

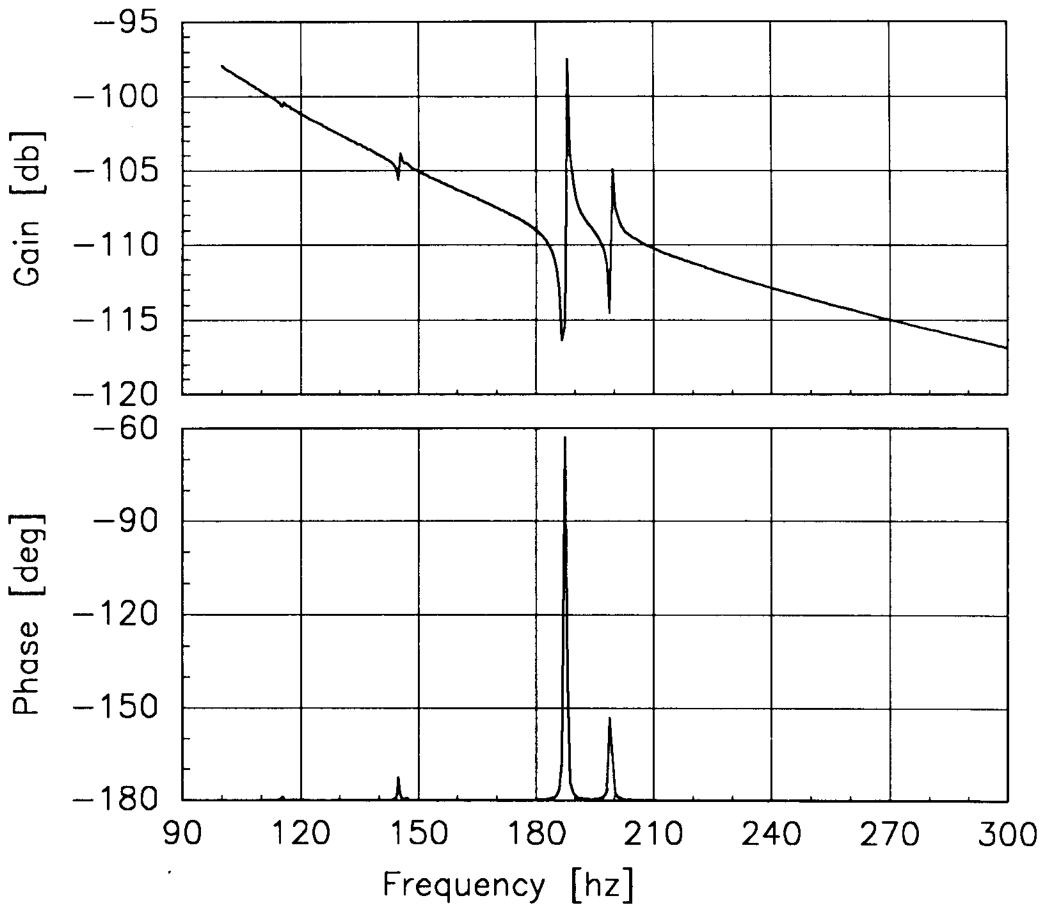


Figure 4: Frequency Response from Motor to Shaft Encoder

Figure 4 is of importance to the control of the system because it is the frequency response of the system as seen by the controller, i.e. from the motor torque to the sensed angle at the encoder. The figure clearly shows two modes which will be excited by the controller, and will therefore react with it. Quantifying the level of structural and controller interaction is one of the key issues which can be addressed using the interface. In this case time domain simulations showed that the level of interaction was acceptable.

This example demonstrates the use of MSC/NASTRAN and $MATRIX_X$ to evaluate the control-structure interaction of a large system. MSC/NASTRAN was used to efficiently reduce the large number of physical degrees of freedom of the full model to a set of modal coordinates. Having this reduced system, the $MATRIX_X$ environment is tailored for fast system evaluations and control design.

6 Extending the Current Interface

The previously described interface allows a structural model to be easily transfered from a structural analysis package to a control design package. It is interesting to ask if there are any potential benefits to designing the structure and controller simultaneously, instead of successively. A great amount of research has been conducted in this area recently, [1]-[6]. Results from one such study [3] are shown in Table 1.

	mean-square value of output jitter	mean-square value of input energy
open-loop	10,015	—
closed-loop on nominal structure	1,133	5.84
closed-loop on the open-loop optimal structure	104.2	0.238
closed-loop on the closed-loop optimal structure	40.96	0.177

Table 1: Mean-square values of outputs and inputs of the structure for a variety of design methods

These results show the open loop disturbance rejection capabilities of a simple truss in open loop and in three closed loop configurations. In all three cases the controller is an optimal quadratic regulator. In the first case the optimal regulator is placed on the nominal open loop system, showing a factor of 9 improvement in performance. In the second case, the open loop disturbance rejection capabilies of the structure are optimized by redistributing mass in the system before the optimal regulator is placed on the system. In this case another factor of about 10 improvement is seen. In the third case the disturbance rejection capabilities of the system are optimized in closed loop. This means that for every structural design evaluated, an optimal controller is in place on the system. As can be seen in the table, a further increase in performance of 2.5 times is achieved.

These results were obtained on an 11 member truss where a closed form solution of the finite element model was easily obtainable. However, for realistic problems a structural analysis program such as MSC/NASTRAN is essential. In this case it is necessary to pass not only the nominal system dynamics, but additional information as well.

The simplest case is the redesign of a medium size system ($\sim$ 100 degrees of freedom) by redistributing mass in the system. In this case the only additional outputs required are the component mass and stiffness matrices. These matrices can be scaled depending on the redistribution of mass in the system, and combined to give the complete system matrices. Such a procedure allows a general nonlinear optimizer such as the one in MATRIX_X to optimize either an open or closed loop performance index for the structure.

In general it is not possible to design a controller for systems of very high order, ie more than a 100 modes. In this case it is necessary to design the controller based on a reduced order model. Therefore, for larger systems an interface should pass some of the system eigenvalues, eigenvectors and their sensitivities with respect to the design parameters. The selection of these modes is in effect a reduction of the model order. These modes can then be updated in a linear manner from the sensitivities during the optimization process in MATRIX_X. In this case it is necessary to obtain a new eigensolution after the system has been perturbed enough that a linear update is no longer accurate. An example of this technique for a flexible space system is given in [4].

7 Conclusions

In this paper a description of an existing interface between MSC/NASTRAN and MATRIX_X has been presented. This interface allows reduced order linear systems to be extracted from the MSC/NASTRAN output file and placed in MATRIX_X input file format. This model can then be used in a straightforward manner for simulation and control design.

An improved interface, which would allow additional information to be transfered, was also described.

8 Acknowledgements

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