Nonlinear Static Analysis of McDonnell Douglas MD90 Aircraft Using MSC/NASTRAN Superelement Database

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ABSTRACT

The new McDonnell Douglas MD90 aircraft engine/pylon/fuselage interface reactions, pylon stresses, and deflections were determined using MSC/NASTRAN nonlinear finite element analysis. The aft fuselage was modeled in detail using McDonnell Douglas interactive CGSA/CASD graphic software and reduced to a boundary stiffness matrix at the fuselage/pylon interface to minimize the cpu time in nonlinear iterations, design optimization, and evaluating multiple load conditions. MSC/NASTRAN was then used for SOL 66 nonlinear static analysis with the detailed engine model represented as one superelement, the pylon/fuselage model as another superelement, and the engine mount structures as residual structure. The engine mount structures were modeled by non-linear gap elements to evaluate the fail-safe design and by thermal elements to account for the preloads caused by engine expansion. The ultimate and fail-safe loading conditions were analyzed for emergency landing, arbitrary dynamic landing, arbitrary vertical gust, arbitrary lateral gust, engine seizure, reverse thrust rollback, take-off run, towing, and taxiing conditions. Fatigue design loads were generated from take-off to landing for one operation cycle. Engine fan blade-out analysis was also performed for the engine mount loads. Deflections of the engine/pylon/fuselage structure were generated to help designers investigate structural clearances for both ultimate and fail-safe design conditions.

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INTRODUCTION

The McDonnell Douglas MD90 family twin-jets are the derivative from the MD80 series aircraft. With the new International Aero Engines (IAE) V2500 engine, the MD90 series aircraft is designed to be more fuel efficient than the MD80 series aircraft. The MD90 family twin-jets includes 114-seat MD90-10, 153-seat MD90-30, and 180-seat MD90-40. First airline delivery is scheduled in the fourth quarter of 1994. Since the new IAE V2500 engine is heavier and provides more thrust than the MD80's JT8D engine, the pylon structure was redesigned and the airframe structure was beefed up for the larger payload. This paper shows the MD90 new pylon finite element model and the fuselage/pylon/engine interface loads and deflections based on MSC/NASTRAN nonlinear static analysis. The superelement database capability was utilized to minimize the computer cpu time during nonlinear iterations.

FINITE-ELEMENT MODEL INTEGRATION

Detailed three-dimensional finite element models of the aircraft fuselage and pylon were first developed using McDonnell Douglas in-house interactive graphic software CGSA/CASD, then translated to the standard MSC/NASTRAN bulk data deck for the finite element solution. The engine finite element model was supplied by the engine vendor IAE and carefully integrated with the fuselage and pylon models using MSC/NASTRAN [1,2,3,4]. Integrated finite element model for the aircraft fuselage/pylon/engine is shown in Figure 1. MSC/NASTRAN's superelement capability with the new automated restart database capability in version 66 was effective to handle the large problem size, and to reduce turnaround and cpu time for numerous loading conditions, in an effort to achieve design economy.

The engine is supported by the forward mount, aft mount, and thrust link mount. The forward mount has upper and lower attachments to a yoke structure which is then connected to the pylon structure to resist the rolling movement of the engine. Engine pitching and yawing movements are taken by the forward and aft mounts. Engine thrust is taken by two thrust links and goes into the pylon structure directly. The engine mount structure is designed to be fail-safe, i.e. when any one of the engine supporting structures fails, there is a parallel load path via substitute structure for the engine loads to transmit from fail-safe structure to pylon for increased reliability. The MD90 engine mount fail-safe philosophy is implemented by the fail-safe bushing/pin design. There are two fail-safe bushing/pin structures in the engine mount, one for the forward mount and one for the aft mount. The forward fail-safe bushing/pin locates in the middle of the upper and lower engine attachments. The fail-safe bushing and supporting pin are separated by a circular air gap to ensure there is no contact between each other during normal (all well) operation. The forward fail-safe bushing will pick up the engine-to-pylon load when either the upper or lower forward mount fails. The aft mount fail-safe bushing/pin locates under the aft mount attachment point to the pylon and transmits loads from the engine to the pylon when the aft mount structure fails. The finite element bushing/pin model was accomplished by placing 12 radial gap elements, at 30 degrees increment, in a cylindrical coordinate system for the air gap between the bushing and pin. Rigid body elements (RBE2) were used to transfer loads from gap elements to the pylon structure (Figure 2). The reaction force distribution between the bushing and supporting pin was obtained as an elliptical shape during contact, as expected in real-life.

Due to the significant engine thermal expansion experienced while operating, such as aircraft parked, engine warm-up, take-off, reverse thrust, and cruise, the forward engine mount attachments can displace in the fore-aft direction with respect to the pylon and alter the engine mounts' fore-aft loads. To simulate this thermal expansion, two equivalent thermal elements were created for the upper and lower forward mounts. The internal self-equilibrating preloads due to the engine thermal expansion were simulated by changing the temperature of these two thermal elements so they would shrink to zero length and develop internal loads between the engine and pylon. The engine mount structures would deflect to the final equilibrium positions under different loading conditions.

In the thrust link isolator structure, gap elements are also used to model the snubbing design when one of the two thrust links fails, i.e. only one thrust link is carrying load, and a huge thrust load is experienced.

NONLINEAR STATIC ANALYSIS (SOL 66)

MSC/NASTRAN SOL 66 capability was useful to simulate the nonlinear characteristics of fail-safe and snubbing design of the MD90 engine mount structure. Gap elements (CGAP) were used for the boundary nonlinearity between the fail-safe supporting pin and bushing; they were also used for the snubbing condition in the thrust link mount. In order to use gap elements and take advange of the new automated restart database capability of superelements in MSC/NASTRAN version 66 and save computer running time, SOL 66, nonlinear static analysis, was used in the present analysis. Several different options of nonlinear analysis control parameter (NLPARM) were attempted to improve the accuracy and convergence speed for this particular problem before production runs were successfully performed. It was found that the Quasi-Newton method with automatic selection of the most efficient strategy option, together with eight load increments gave very good results for all loading conditions. The convergence checks were performed based on the displacement, load equilibrium, and work error tests. With eight load increments, it only took four iterations to converge in each load increment in the present study.

With the large displacement parameter card (PARM,LGDISP,1) option, the force equilibrium was based on the final deformed position, in the case of geometric nonlinearity.

DATABASE IMPROVEMENT

At Douglas Aircraft Company, MSC/NASTRAN is available on both IBM 3090 for large production runs and Micro VAX-II for reduced size jobs. In the present analysis, superelements, such as fuselage, pylon, and engine models, are stored in a database to save computational time for restarting. Since the fuselage is symmetric with respect to the center plane, only half of the fuselage structure is modeled. The fuselage model is composed of 10000 degrees of freedom, the pylon model 4000 degrees of freedom, and the engine model 13000 degrees of freedom. By using the detailed fuselage model, accurate load paths from the pylon structure to the fuselage were obtained. In order to improve cpu time further more, we applied the static condensation technique on some of the superelements like the engine and fuselage models [5,6,7,8]. Since we were not interested in recovery of the stress distribution of the engine structures, the engine model was reduced to the engine mount interface points, which only contained 54 degrees of freedom. By doing this the problem size was reduced substantially. It was also found that changing fuselage structures had very little effect on the engine mount loads and deflections, so a similar reduction technique was applied to the fuselage model for the fuselage/pylon interface points. Since the reduced stiffness matrix derived from static condensation was exact at those interface points, the same results were expected by using the reduced stiffness matrix as compared with using the full model in analysis. The cpu time savings was at least ten times by using the static condensation technique. The condensed stiffness matrix was obtained by using an analysis set (ASET1) on the interface grids and running MSC/NASTRAN to generate it. The reduced stiffness K_{aa} was output either in standard MSC/NASTRAN DMIG cards or in FORTRAN readable binary file (OUTPUT4) format. The reduced stiffness matrices of different superelements were then input by using K2GG option in case control deck for DMIG input (Table 1), or by using INPUTT4 DMAP alter to read in binary files (Table 2).

Alternately, general element (GENEL) cards for the stiffness matrix were generated at the models' interface to save computer running time. The GENEL matrix bulk data cards for the superelement finite element model can be generated from inhouse CGSA/CASD database shared by MD90 product definition and manufacturing groups.

Reduced stiffness matrices were stored in different files and called in to the model by using INCLUDE cards in bulk data deck. This splits a big input file into several small files and makes file editing faster and easier. By using "ECHO=NONE" in MSC/NASTRAN case control deck, the unwanted output listing of the model was suppressed.

MODEL VALIDATION

Finite element model validation usually requires correlation between analytical results and experimental/flight test data on static components' deflections and loads, and often it requires structural optimization and vibration correlation as well [9,10]. Though the complete MD90 test aircraft will not be produced until 1994, MD90 pylon and fuselage design is similar to MD80/DC-9 counterparts which have been certified and in flight for over decades, making it adequate to evaluate the results against the MD80/DC-9 service data. With the lessons learned in design modifications and model enhancements from MD80/DC-9, which was included in the present investigation, the analytical predictions will show improved correlation.

The nonlinear static analysis results were also checked with linear static analysis (SOL 24) results by deactivating CGAP elements and the superelement database capability in the same model used in the nonlinear analysis. Again, good comparisons were found between linear and nonlinear results when nonlinear effects, such as gap elements and large deflection option, were not active, validating the developed superelement synthesis strategy.

The effects of merging symmetric substructures, taking image of the left engine, left pylon, and left gap mounts, investigating symmetric and anti-symmetric loads, were carefully evaluated to correctly perform analysis of the complete equivalent aircraft finite element model.

RESULTS

MD90 pylon/engine interface loads and displacements were generated using finite element analysis. The stress distributions of the pylon and forward engine mount yoke structures were also calculated to improve design of the new pylon/yoke structures. Element stresses, such as von Mises stress, maximum shear stress, and maximum principal stress, were plotted using PDA/PATRAN2 post-processor software on a Silicon Graphics workstation. Structures which had high stress levels were redesigned to ensure acceptable stress distribution. Deflections of structures were checked for the tolerance and manufacturing producibility of structural parts.

Since the fail-safe bushings were modelled by 12 radial gap elements at 30 degree increments, it seems theoretically necessary to adjust the gap elements' stiffness to compensate for the changing number of closing gaps. It was found that adjusting radial gap stiffness with several gaps in contact did not appreciably affect the reaction forces on the pylon/engine interface, indicating weak nonlinearity and satisfactory performance of the CGAP elements in our application. Neither the reactions nor the deflections of the pylon/engine interface structures were influenced much because the bushing stiffness is high compared to the other interface or supporting structures.

Engine mount ultimate design (load factor = 1.5) loads and deflections were calculated for the conditions when the engine mount structures were intact. Engine mount fail-safe design loads and deflections were calculated when either the upper forward mount, or lower forward mount, or aft mount, or thrust link failed. Engine mount fatigue design loads were calculated for one airplane operation cycle, i.e. from take-off to landing. Engine mount design loads for mass imbalanced load from engine fan blade-out loading conditions were also calculated. Restarting with the MSC/NASTRAN superelement database was both effective and efficient to expedite design iterations under numerous loading variations.

CONCLUSION

Use of MSC/NASTRAN SOL66 for the MD90 program provided a cost-effective timely solution of nonlinear static problems. This paper shows how circular gap and snubbing design were accomplished by using CGAP elements, and how internal preloads were obtained by using thermal elements in the model. Boundary stiffness matrix and superelement capability were successfully employed to achieve design economy, in consideration of meeting production schedule within cost.

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REFERENCES

[1] Herting D., "MSC/NASTRAN Nonlinear Course Notes," The MacNeal-Schwendler Corporation, Los Angeles, CA, 1987.

[2] Palacol E., "Advanced Nastran Nonlinear Analysis Class Lectures," Douglas Aircraft Company, 1990.

[3] "MSC/NASTRAN User's Manual, Version 66, The MacNeal-Schwendler Corporation, Los Angeles, CA, November 1988."

[4] "MSC/NASTRAN Application Manual, Version 66, The MacNeal-Schwendler Corporation, Los Angeles, CA, November 1988."

[5] Bathe, K.-J., Finite Element Procedures in Engineering analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1982.

[6] Zienkiewicz, O. C., The Finite Element Method, 3rd Edition, McGraw-Hill, New York, 1977.

[7] Bathe, K.-J. and Wilson, E. L., Numerical Methods in Finite Element Analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1976.

[8] Hughes, T. J. R., The Finite Element Method Linear Static and Dynamic Finite Element Analysis, Prentice-Hall, Inc., Englewood Cliffs, New Jersey, 1987.

[9] Gupta, V. K., "Structural Optimization Using NASTRAN," 16th NASTRAN User's Colloquium, NASA Conference Publication No. 2505, pp. 64-78, Arlington, VA, April 25-29, 1988.

[10] Gupta, V. K., Newell, J. F., and Roberts, W. H., "Band Lanczos Vibration Analyses of Aerospace Structures," Symposium on Parallel Methods for Large-Scale Structural Analysis and Physics Applications, NASA Langley Research Center, Hampton, VA, Feb. 5-6, 1991.

TABLE 1

Sample NASTRAN file for mass and stiffness matrices input in DMIG form

```
ASSIGN MASTER=ORIGINAL.MASTER
INIT DBALL LOGICAL=(DBALL(40000))
ID TOM,WU  $ OCT 90
SOL 66
$RESTART VERSION=1,KEEP  $ MOVE THESE TWO LINES AFTER ASSIGN MASTER=...
$DBCLEAN,VERSION=4       $ AND DELETE INIT DBALL...  FOR RESTART
DIAG 50
TIME 999
CEND
TITLE= ORIGINAL MODEL + DMIG INPUT
ECHO=NONE
K2GG=K2AC
M2GG=M2AC
DISPLACEMENT=ALL
SEALL=ALL
SUBCASE 11
NLPARM=10
LOAD = 11
$
BEGIN BULK
PARAM   AUTOSPC YES
PARAM,WTMASS,.00259
PARAM,COUPMASS,1
PARAM,LGDISP,1
NLPARM,10,8,0.,AUTOQN,1,20,UPW,NO,+NL1
+NL1,1.0E-4,1.0E-8,1.0E-12,5
$================
$  ORIGINAL MODEL
$================
.......
$
$====================
$  DMIG K AND M INPUT
$====================
DMIG    K2AC           0       6       2       0
DMIG*   K2AC                           1               1
*                      1               1-2.683456966D-01
.......
DMIG    M2AC           0       6       2       0
DMIG*   M2AC                           1               1
*                      1               1 6.173513470D+01
.......
ENDDATA
```

TABLE 2

Sample NASTRAN file for mass and stiffness matrices input in binary form

```
ASSIGN MASTER=ORIGINAL.MASTER
ASSIGN INPUTT4=K2AC.BIN,UNIT=51
ASSIGN INPUTT4=M2AC.BIN,UNIT=52
INIT DBALL LOGICAL=(DBALL(40000))
ID TOM,WU  $ OCT 90
SOL 66
$RESTART VERSION=1,KEEP  $ MOVE THESE TWO LINES AFTER ASSIGN MASTER=...
$DBCLEAN,VERSION=4       $ AND DELETE INIT DBALL...  FOR RESTART
DIAG 50
TIME 999
COMPILE DMAP=SOL66,SOUIN=MSCSOU,NOLIST,NOREF $
$ ====================================
$ MSC/NASTRAN DMAP ALTER FOR SOL66
$ USE TO INPUT BINARY MASS & STIFFNESS
$ MATRICES (M2AC & K2AC)
$ (MSC/NASTRAN V.66)
$ ====================================
ALTER 510 $ SOL66, V66;    USE ALTER 321 FOR SOL66, V65
MTRXIN,    ,MATPOOL,EQEXINS,SILS,/GSTIFG,,/V,N,LUSETS/S,N,LMON1 $
COND FINIS,LMON1 $
TRNSP  GSTIFG/GSTIFGT $
INPUTT4 /K2AC,,,,/1/51/-2 $
INPUTT4 /M2AC,,,,/1/52/-2 $
$
SMPYAD GSTIFG,K2AC,GSTIFGT,,,KJJX/LKDD/3 $
MODTRL LKDD////6 $
EQUIV LKDD,KJJX/ALWAYS $
$
SMPYAD GSTIFG,M2AC,GSTIFGT,,,MJJX/LMDD/3 $
MODTRL LMDD////6 $
EQUIV LMDD,MJJX/ALWAYS $
$
CEND
TITLE= ORIGINAL MODEL + BINARY INPUT
ECHO=NONE
DISPLACEMENT=ALL
SEALL=ALL
SUBCASE 11
NLPARM=10
LOAD = 11
$
BEGIN BULK
PARAM   AUTOSPC YES
PARAM,WTMASS,.00259
```

```
PARAM,COUPMASS,1
PARAM,LGDISP,1
NLPARM,10,8,0.,AUTOQN,1,20,UPW,NO,+NL1
+NL1,1.0E-4,1.0E-8,1.0E-12,5
$
$================
$  ORIGINAL MODEL
$================
.......
$
$====================================
$  DMIG UNIT MATRIX FORT BINARY INPUT
$====================================
DMIG    GSTIFG  0       9       1       0
DMIG    GSTIFG  1       1               1       1       1.0
DMIG    GSTIFG  1       2               1       2       1.0
DMIG    GSTIFG  1       3               1       3       1.0
DMIG    GSTIFG  1       4               1       4       1.0
DMIG    GSTIFG  1       5               1       5       1.0
DMIG    GSTIFG  1       6               1       6       1.0
DMIG    GSTIFG  2       1               2       1       1.0
DMIG    GSTIFG  2       2               2       2       1.0
DMIG    GSTIFG  2       3               2       3       1.0
DMIG    GSTIFG  2       4               2       4       1.0
DMIG    GSTIFG  2       5               2       5       1.0
DMIG    GSTIFG  2       6               2       6       1.0
.......
ENDDATA
```

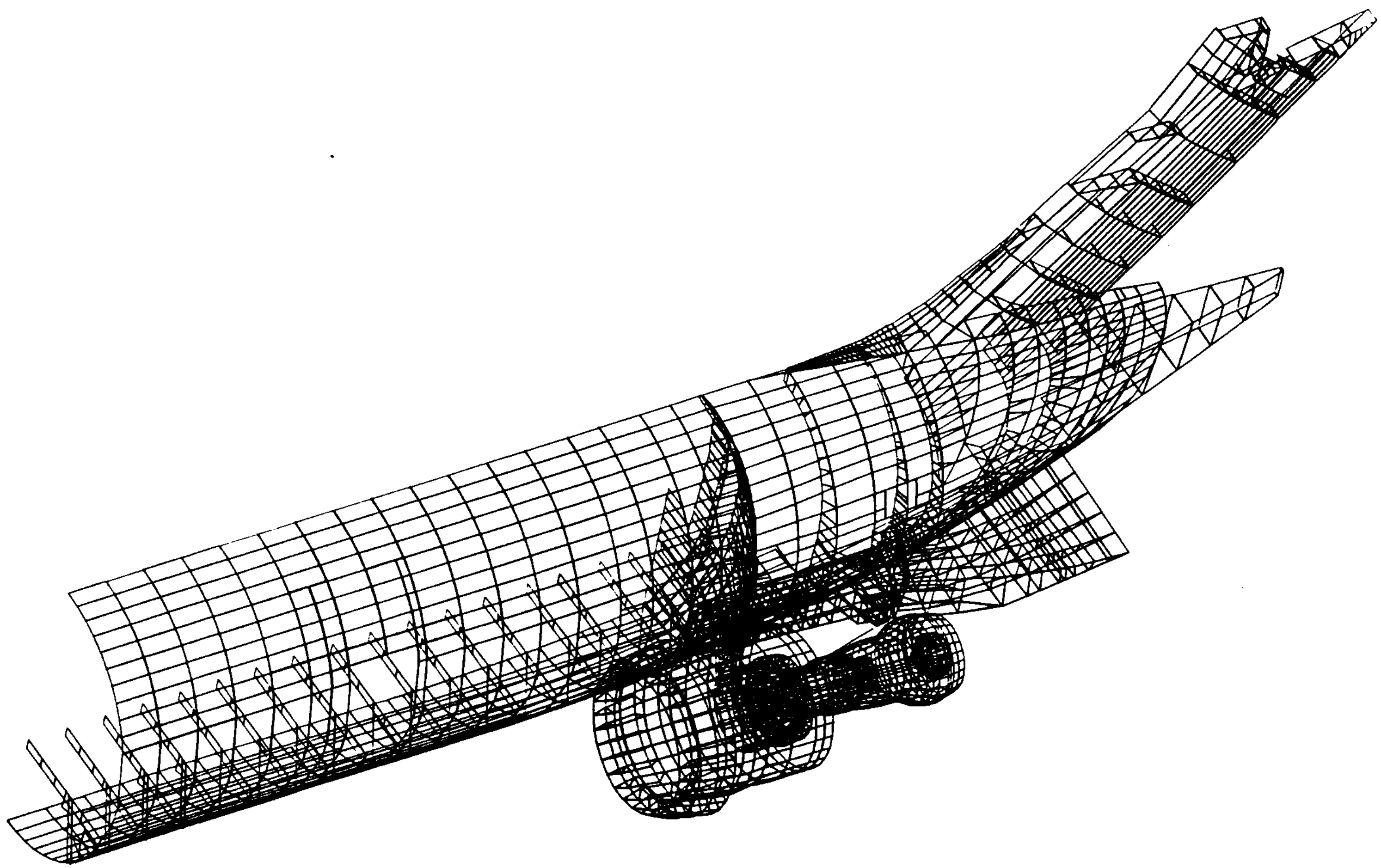

Figure 1. Integration of finite element model of MD90 fuselage/pylon/engine.

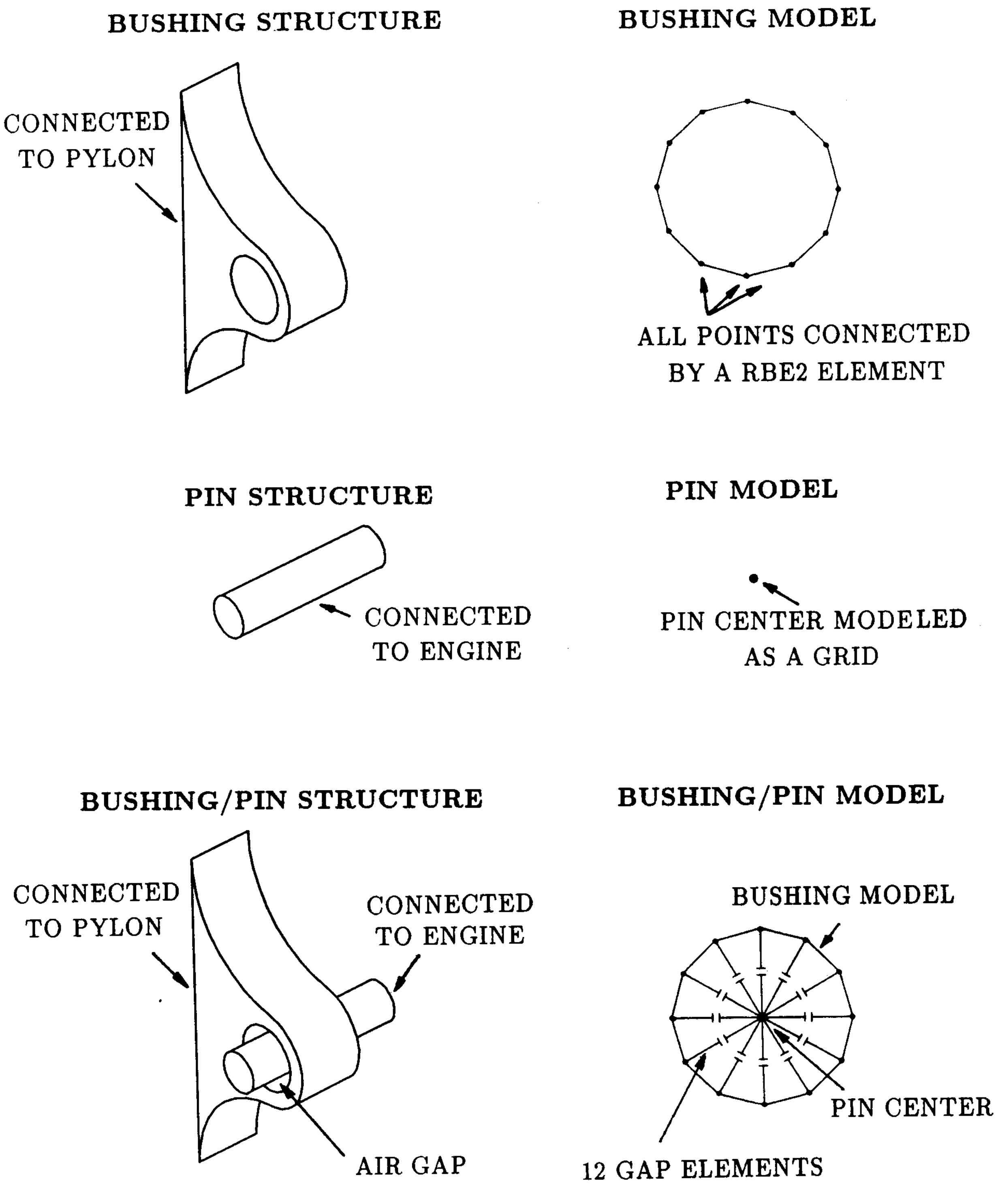

Figure 2. Illustration of aft mount fail-safe bushing/pin modeling.