THE SPAR THERMAL ANALYZER - PRESENT AND FUTURE

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SPAR THERMAL ANALYZER

To provide a general in-house integrated thermal-structural analysis capability the Langley Research Center is having the SPAR Thermal Analyzer (fig. 1) developed under contract by Engineering Information Systems, Inc. The SPAR Thermal Analyzer is a system of finite-element processors for performing steady-state and transient thermal analyses. The processors communicate with each other through the SPAR random access data base. As each processor is executed, all pertinent source data is extracted from the data base and results are stored in the data base.

The tabular input (TAB), element definition (ELD) and arithmetic utility system (AUS) processors are used to describe the finite element model. The data base utility (DCU) processor operates on the data base. The plotting processors (PLTA, PLTB) provide the capability to plot the finite element model for model verification but do not directly plot temperatures. The thermal geometry (TGEO) processor performs geometry checking of the thermal elements and total model. The thermal processors for steady state analysis (SSTA) and transient analysis (TRTA, TRTB and TRTG) are described in References 1 and 2. In addition there are several processors not shown in the figure for extraction of thermal fluxes, system matrices and system operating characteristics.

On a scalar computer the processors may be executed interactively or in a batch mode. A typical analysis is usually performed as a sequence of interactive and batch operations where model development and verification is performed interactively and actual thermal calculations performed in batch mode. The program operates on UNIVAC, CDC, PRIME and VAX computers.

SPAR THERMAL ANALYZER

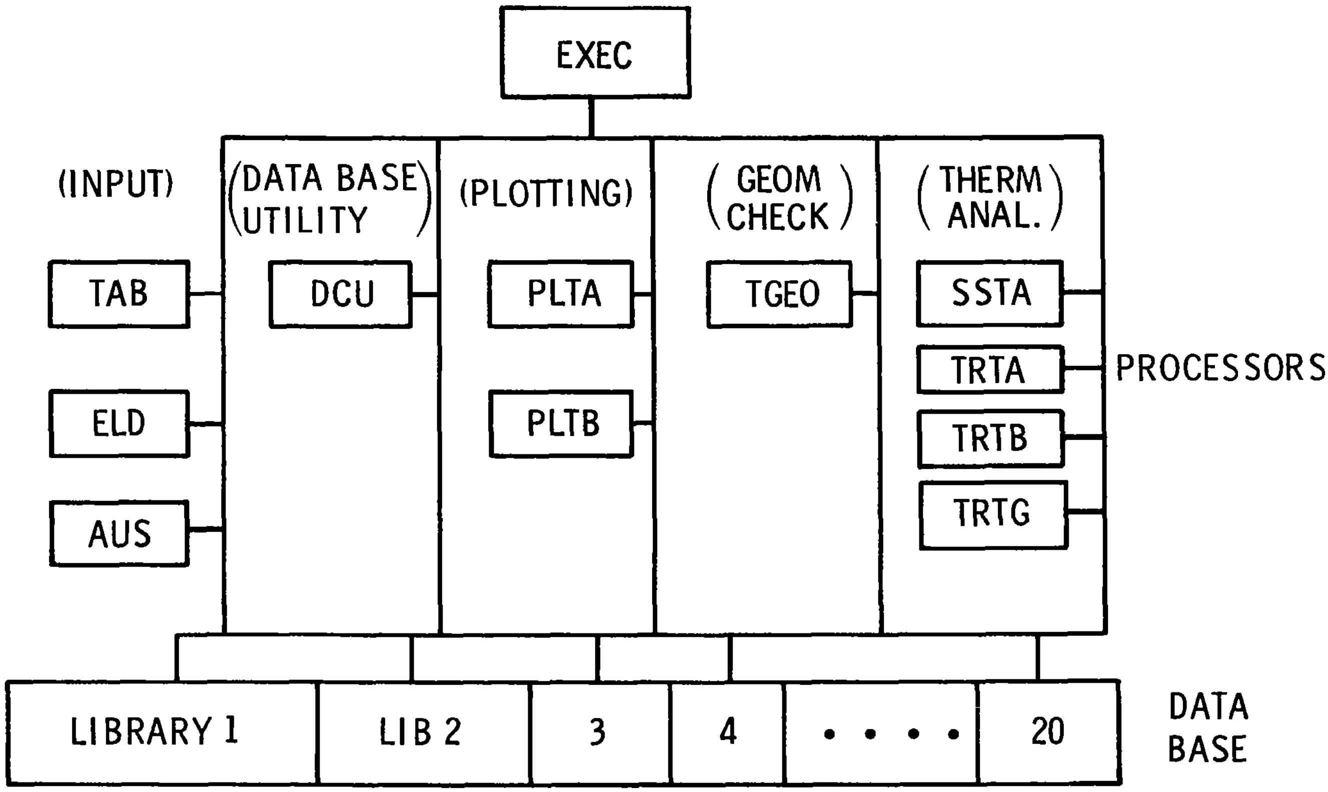


Figure 1

DATA BASE

The SPAR data base (fig. 2) stores all the program data and provides for data transfer between processors. The DCU processor permits the user to access data in the data base. The table of contents (TOC) function produces a twelve word record for each data entry that includes date and time of creation, four word data name, type, length, block size and error code. Additional data documentation is available through the use of text data sets which may be used to describe the problem solution. Restart capability is provided by saving one or more libraries on a disk file or a restart tape. The program can be restarted after any processor execution. In addition, DCU permits the transfer of data to or from a file external to the SPAR data base and allows condensing several libraries into one library for storage. The maximum size of the data base on CDC equipment is a maximum of 10 libraries of 2048 data sets per library. Use of libraries containing a large number of data sets increases I/O costs.

In addition to the DCU function described above, AUS permits the definition of arbitrary data sets for entry into the data base. In the SPAR Thermal Analyzer, AUS is used to define material properties, thermal loads and element properties. AUS also allows the transfer of all or part of one data set to another as well as performing arithmetic and other functional operations on applicable data in the data base.

- STORES ALL DATA
- DATA TRANSFER BETWEEN PROCESSORS
- DOCUMENTS CONTENTS

  TABLE OF CONTENTS (DATE, TIME, TYPE, SIZE, NAME)
  TEXT DATA SETS
- RESTART CAPABILITY (FILE OR TAPE)
- TRANSFER DATA TO/FROM EXTERNAL FILE
- ALL DATA ACCESSIBLE
- MAX SIZE (CDC), 10 LIB, 2048 REC/LIB
- LARGE NO. ENTRIES PER LIB. INCREASES I/O COST

Figure 2

ELEMENT REPERTOIRE

Several element types are included in the SPAR Thermal Analyzer to model the different heat transfer functions and the storage of heat (fig. 3). The K21, K31, K41, K61 and K81 elements model conduction and heat capacity. These are isoparametric elements which have a consistent capacitance matrix and are bounded by 1 or 2 nodes for one dimensional elements, 3 or 4 nodes for two dimensional elements and 6 or 8 nodes for three dimensional elements. A "zero-length" form of the 2-D element is used with a default length of unity to provide a lumped capacitance. All temperature dependent element properties are based on the average element temperature.

Two types of convective elements are included. The C21, C31 and C41 elements model convective heat transfer between a surface and a medium at a known temperature which may be time dependent. Convective exchange between a surface and a medium at an unknown temperature is modeled by the C32 (2 surface nodes (SN), 1 fluid node (FN)), C42 (2SN, 2FN) and C62 (4SN, 2FN) elements.

A two node mass-transport element with fluid conduction (MT21 element) is available in either a conventional or variably up-winded formulation. Combined mass-transport, convective-exchange elements are the MT42 (2SN, 2FN) and the MT62 (4SN, 2FN) elements which model typical pipe and plate-fin flow passage configurations.

The radiation-exchange elements are the R21 (1 or 2 SN, 1-D), R31 (3SN, 2-D) and R41 (4SN, 2-D) elements. In addition there is an experimental element capability that provides the user with the capability to include an element having from 2 to 32 nodes. This requires the user to insert the coding for the element in the proper subroutines, compile those subroutines and load the program. This capability was provided to allow check-out of new element formulations, but it can also be used to include capabilities not present in the program.

FUNCTION	NODES	COMMENTS
• CONDUCTION-CAPACITY	1, 2, 3, 4, 6, 8	ISOPARAMETRIC * CONSISTENT CAPACITANCE
• FORCED CONVECTION	1, 2, 3, 4	PRESCRIBED CONVECTIVE TEMP
• FLUID SURFACE CONVECTION	3, 4, 6	UNKNOWN CONVECTIVE TEMP
• MASS TRANSPORT	2	CONVENTIONAL OR UPWINDED FORMULATION
• COMBINED MASS-TRANSPORT AND CONVECTION	4, 6	
• RADIATION	1, 2, 3, 4	USER SUPPLIED SHAPE FACTORS
• EXPERIMENTAL	2 - 32	ELEMENT CHECK OUT, USER FORMULATION

* ALL ELEMENT PROPERTIES BASED ON AVERAGE ELEMENT TEMPERATURE

Figure 3

MATERIAL PROPERTIES

Thermal conductivity may be anisotropic with the specification of six terms to describe conductivity. Thermal conductivity, density, specific heat and convection coefficients may be temperature, time and pressure dependent. The properties affecting radiation, emissivity, reflectivity and transmissivity, may be temperature and time dependent. (See fig. 4.)

• CONDUCTIVITY	ANISOTROPIC TEMPERATURE DEPENDENT TIME DEPENDENT PRESSURE DEPENDENT
• DENSITY SPECIFIC HEAT CONVECTION COEFFICIENTS	TEMPERATURE DEPENDENT TIME DEPENDENT PRESSURE DEPENDENT
• EMISSIVITY REFLECTIVITY TRANSMISSIVITY	TEMPERATURE DEPENDENT TIME DEPENDENT

Figure 4

BOUNDARY CONDITIONS AND THERMAL EXCITATION

The boundary conditions that may be specified include time-dependent nodal temperatures, convective exchange temperatures and mass transport rates (fig. 5). The imposed thermal excitation can consist of time and temperature dependent surface heat fluxes, volumetric heat generation and time dependent incident radiative heat fluxes. "Perfect" conductors are available to force two separate nodes to have the same temperature.

- PRESCRIBED, TIME-DEPENDENT TEMPERATURES
- CONVECTIVE EXCHANGE TEMPERATURES - TIME DEP.
- "PERFECT" CONDUCTORS - ENFORCED TEMPERATURES
- SURFACE HEAT FLUX - TIME OR TEMPERATURE DEP.
- VOLUMETRIC HEAT GEN. - TIME OR TEMPERATURE DEP.
- PRESCRIBED, TIME DEPENDENT RADIATION FLUX
- PRESCRIBED, TIME DEPENDENT MASS TRANSPORT RATE

Figure 5

RADIATION EXCHANGE

The radiation heat transfer model assumes that the radiating element is at a uniform temperature with uniform emissive power and incident heat flux (fig. 6). Surfaces emit and absorb diffusely and reflect diffusely and/or specularly. Complete radiation exchange factors or script F factors may be used and the complete matrix must be input since the program does not calculate the exchange factors or assume symmetry of the factor matrix. There is no specific limit on the number of radiating surfaces in a problem but the size of the exchange factor matrix may become so large that several data sets are required. The radiation contribution to the total "conductance" matrix is a diagonal term. When complete exchange factors are used, the radiation load vector is calculated by an iterative solution of the incident heat equation which usually converges in 2 to 10 iterations.

- RADIATION ELEMENTS - RADIATING SURFACE WITH UNIFORM EMISSIVE POWER AND INCIDENT HEAT FLUX
- SURFACES EMIT AND ABSORB DIFFUSELY, REFLECT DIFFUSELY AND/OR SPECULARLY
- COMPLETE EXCHANGE OR SCRIPT F FACTORS MAY BE USED
- NO LIMIT ON NUMBER OF RADIATING SURFACES
- RADIATION K MATRIX IS DIAGONAL
- RADIATION LOAD VECTOR - COMPLETE EXCHANGE FACTOR

  ITERATIVE SOLUTION TO INCIDENT HEAT EQUATION
  USUALLY CONVERGES IN 2 TO 10 ITERATIONS

Figure 6

SSTA

The SSTA processor calculates steady state nodal temperatures (fig. 7). The governing equation is

$$(K_k + K_h + K_r + K_m)T = Q + H + R$$

where K_k, K_h and K_r are the symmetric conduction, convection and radiation matrices and K_m is the asymmetric mass transport matrix, T is the nodal temperature vector and Q, H and R are the source, convection and radiation load vectors. A direct linear solution is performed when there are no radiation or temperature dependent properties. If there are temperature dependent material properties or radiation present a nonlinear solution is performed using a modified Newton-Raphson method. A good procedure is to perform a linear analysis to obtain a starting estimate of the temperature for the nonlinear solution. Through processor RESET controls the user can control factoring of the total matrix and the number of iterations performed between factorings for nonlinear analysis.

- LINEAR AND NONLINEAR STEADY STATE ANALYSIS OF
  $(K_k + K_h + K_r + K_m)T = Q + H + R$
- LINEAR SOLUTION

  NO RADIATION, NO TEMP DEPENDENCY
- NONLINEAR SOLUTION

  MODIFIED NEWTON-RAPHSON
  USER CONTROL - FACTORING AND ITERATIONS

Figure 7

TRTA

The TRTA processor (fig. 8) calculates transient temperature distributions in structures using an explicit algorithm based on a Taylor series expansion solution of the governing equation

$$(K_k + K_n + K_r + K_m)T + C\dot{T} = Q + H + R.$$

In this equation, C is a diagonal (lumped) heat capacitance matrix, $\dot{T}$ is a vector of the first derivative of nodal temperature with respect to time and the remaining terms are as defined for the previous figure. The time step, DT, used in the solution process is calculated automatically to assure stability of the solution. The user specifies the times at which nonlinear effects such as temperature dependent material properties and the radiation contribution, R, are recalculated. Recalculation of the conduction matrices for the 4, 6 and 8 node elements required when the material properties are temperature dependent is performed by scaling when the material properties are isotropic. "Arithmetic" node (nodes with negligible capacitance) capability is available in TRTA. The solution process may be easily restarted from any point in time for which a temperature distribution is available.

- EXPLICIT TRANSIENT THERMAL ANALYSIS BASED ON TAYLOR SERIES EXPANSION SOLUTION OF $(K_k + K_n + K_r + K_m)T + C\dot{T} = Q + H + R$
- AUTO CALCULATION OF DT
- ELEMENT PROP RECOMPUTED AS SPECIFIED BY USER
- CONDUCTION MATRIX FOR 4, 6, 8 NODE ELEMENTS SCALED IF ISOTROPIC
- "ARITHMETIC" NODES (ZERO CAPACITANCE)
- LUMPED CAPACITANCE MATRIX
- RESTART FROM ANY POINT IN TIME

Figure 8

TRTB AND TRTG

These two processors calculate transient temperature distributions using implicit solution algorithms (fig. 9). TRTB uses a Galerkin method with a variable weighted residual parameter, β, which may be set by the user. Different values of β correspond to the following algorithms

β = 1/2, Crank-Nicholson
β = 2/3, Galerkin
β = 1, Backward differences

The user must select the value of DT and the recalculation times for temperature-dependent material properties and radiation load vector. TRTB uses a diagonal (lumped) heat capacitance matrix.

The TRTG processor uses the Lawrence Livermore Laboratories packaged GEARIB algorithms based on the development by W. C. Gear of the University of Illinois. The user may select either of two variable order solution algorithms. The backward difference algorithm is usually chosen for stiff problems and the Adams-Moulton for non-stiff problems. The TRTG processor automatically determines DT and property recalculation times and uses either a diagonal or consistent heat capacitance matrix.

- IMPLICIT TRANSIENT ANALYSIS
- TRTB - GALERKIN WITH VARIABLE PARAMETER
  - USER SELECTS DT AND K MATRIX RECOMPUTATION TIME
  - LUMPED CAPACITANCE MATRIX
- TRTG - BASED ON LLL GEARIB PACKAGE
  - VARIABLE ORDER ADAMS-MOULTON OR BACKWARD DIFFERENCE ALGORITHM
  - AUTOMATICALLY CALCULATES DT AND K MATRIX
  - CONSISTENT OR LUMPED CAPACITANCE MATRIX

Figure 9

TYPICAL TRANSIENT ANALYSIS DATA FLOW

The flow of data in a typical transient thermal analyses is shown in figure 10. While the data base is not shown in the figure, the data input by the user, with the exception of individual processor control commands, and all data created by the processors, with the exception of the actual plot vector file, reside in the data base.

The processors used in the model definition and checking phase and their data outputs are:

TAB - node (joint) locations
AUS - thermal and element section properties
ELD - element definition
PLTA, PLTB - model plots
TGEO - degree of freedom list compiled in checking element geometry

The processors used in the transient-thermal analysis include AUS and one of the transient analyses processors (TRTA, TRTB or TRTG). AUS is used to input the thermal excitation, boundary conditions and define arithmetic nodes if used. The transient analysis processor produces structural temperature distributions for times specified by the user. Printing of the temperatures is accomplished by the DCU processor (not shown).

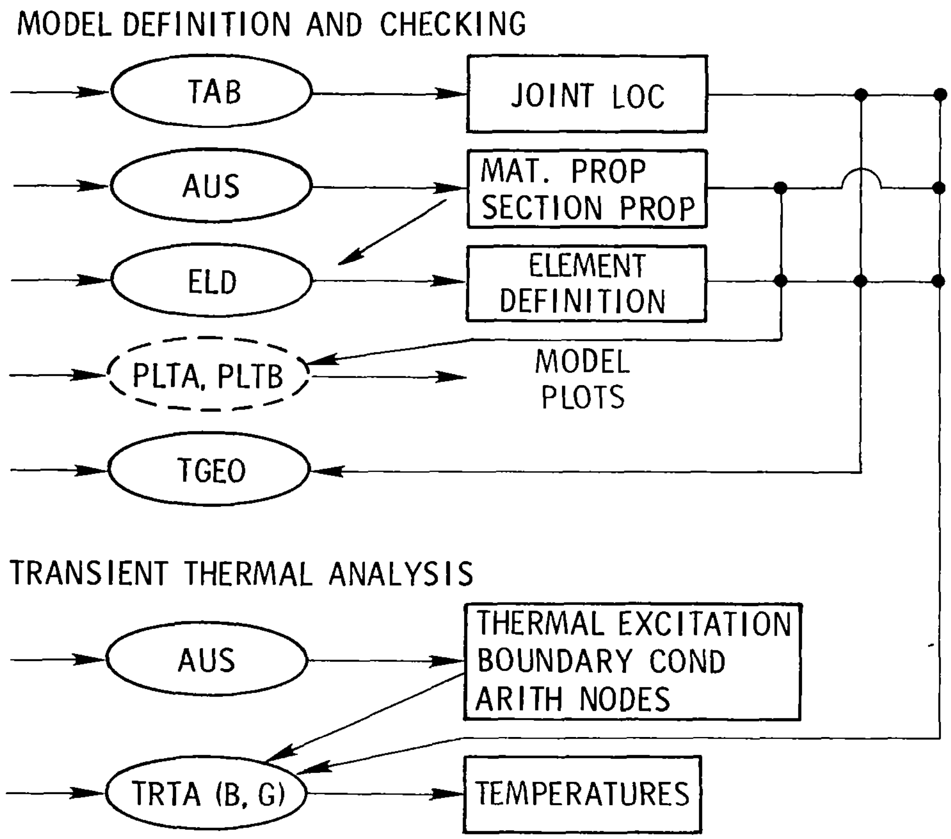


Figure 10

NATIONAL TRANSONIC FACILITY DOWNSTREAM NACELLE

A recent application of the SPAR Thermal Analyzer was part of the certification of the Langley National Transonic Facility (NTF). The NTF is a cryogenic, transonic wind tunnel using nitrogen as a test medium. Since the test medium can vary in temperature from 88 K (-300°F) to 340 K (150°F), transient temperatures of the nacelle and its supporting strut were required to determine thermal stresses.

Figure 11 shows the finite element model used to determine transient temperatures in the downstream nacelle of the NTF at Langley. The model has 2300 nodes and 6100 elements; 2000 time steps (DT) were used in the analysis.

The conduction elements of the thermal finite element model were the same as the structural elements in the structural finite element model. In addition, convection elements were added to the outside of the horizontal strut and outside and inside of the nacelle.

THERMAL MODEL

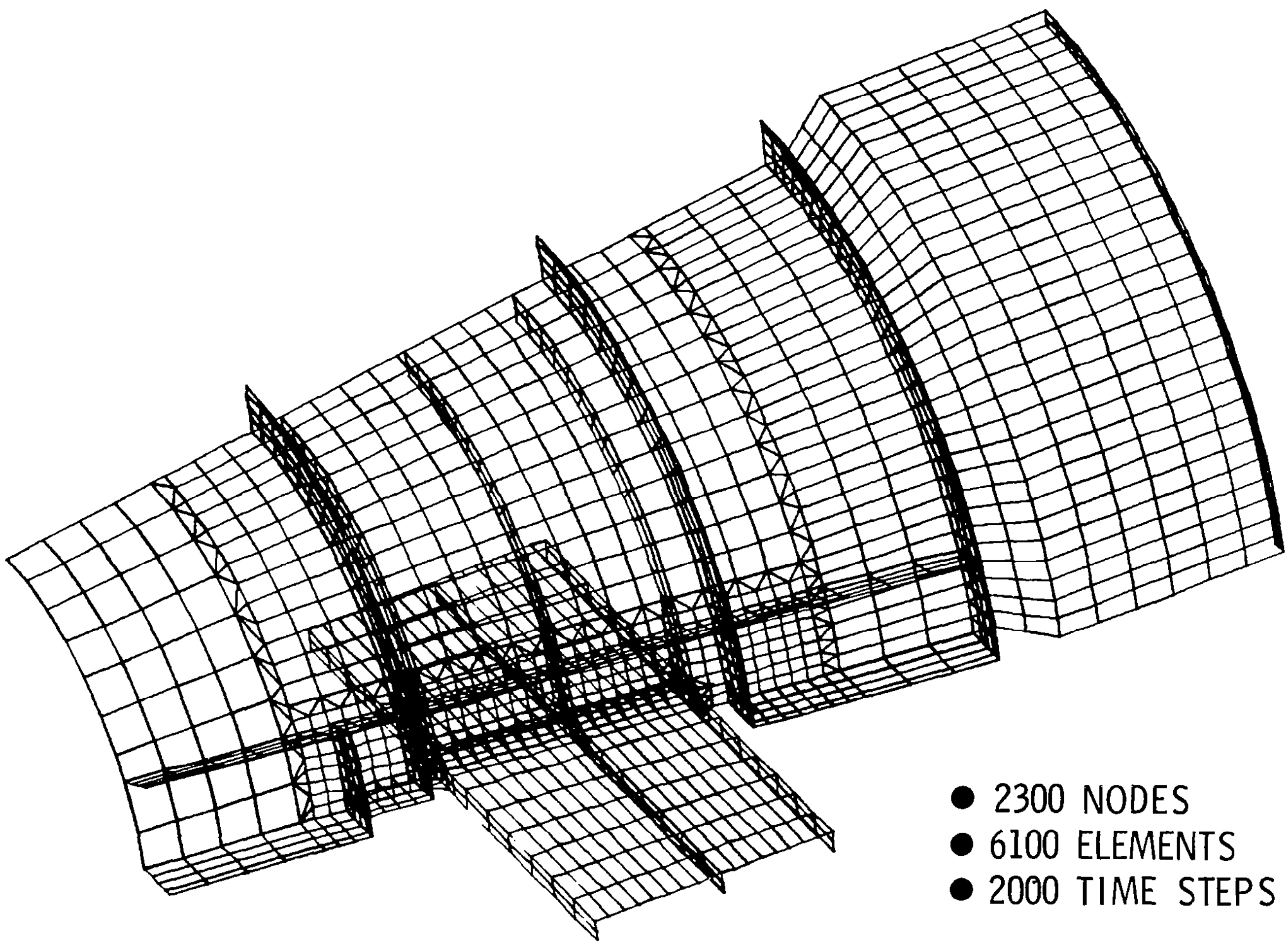


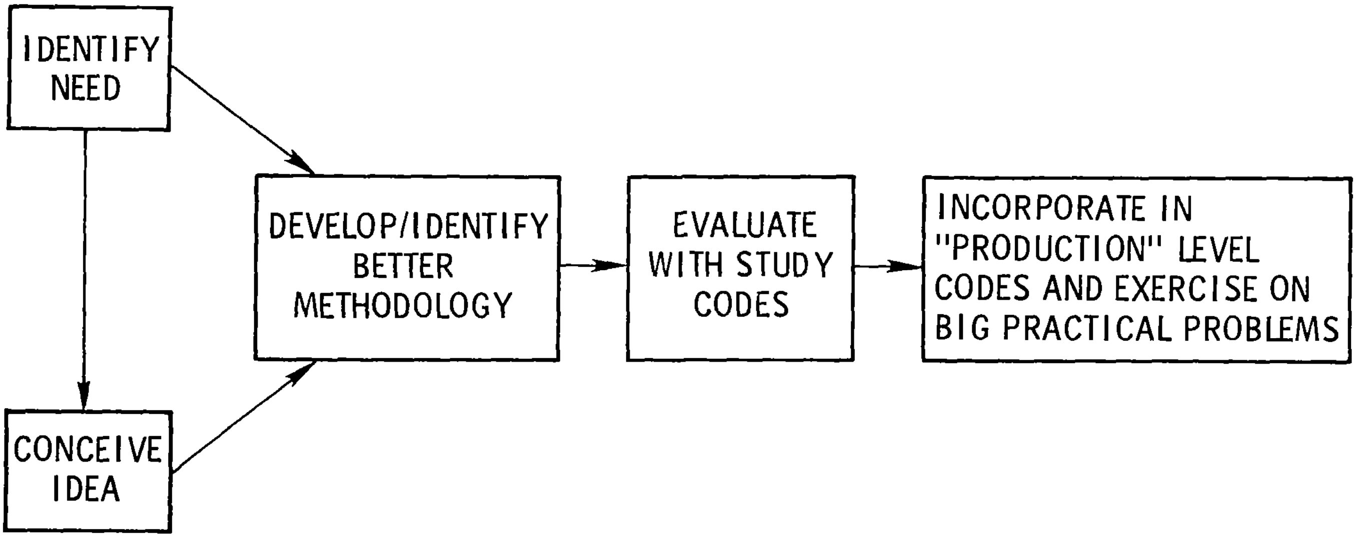
Figure 11

THERMAL-STRUCTURAL ANALYSIS METHODOLOGY

The strategy for improving thermal-structural analysis capability is shown in the chain of boxes in the upper part of figure 12. From the left, there is the identification of a need and conception of an idea to fill that need. This leads to development or identification of a better methodology which is the complete definition of the method to apply the original idea. This method is then evaluated in a study code which allows numerical experimentation with the least amount of effort and greatest opportunity for experimentation. Those methods that prove worthwhile are then incorporated in a "production" code and evaluated on large scale problems.

Some of the ideas presently in varying stages of the development process for possible incorporation into SPAR are shown in the lower portion of the figure. Ideas that are being reported elsewhere in this symposium are identified with the authors name. These include radiation view factor calculation, improved nonlinear equation solution methods, use of a vector computer, switching in the GEAR method, reduced basis technique and integrated thermal-structural elements.

OVERALL APPROACH



RADIATION VIEW FACTORS (EMERY)
IMPROVED NONLINEAR EQUATION SOLUTION METHODS (HAFTKA AND KADIVAR)
VECTOR COMPUTER EVALUATION (ROBINSON, RILEY AND HAFTKA)
SWITCHING IN GEAR PACKAGE
REDUCED BASIS (SHORE)
INTEGRATED THERMAL-STRUCTURAL ELEMENTS (THORNTON)

Figure 12

POSSIBLE NEW CAPABILITY

The possible near-term new capabilities to be added to the SPAR Thermal Analyzer include radiation view factor calculation, solution logic capability and thermal-structural model data transfer (fig. 13). The radiation view factor computation method to be placed in SPAR is discussed by Emery in a another paper in the symposium.

Solution logic capability permits the analyst to supply Fortran code that modifies or can modify the solution process at each time step. Similar capability presently exists to modify the solution at each time that the conductance matrix is recalculated through the use of the experimental element capability. Solution logic capability and use of experimental elements requires recompilation of parts of the program and reloading.

When the thermal and structural finite-element models use the same node numbers and locations, transfer of temperature data to the structural model simply requires renaming a data set. Quite often, however, disciplinary requirements cause the two models to be different. In this case, transfer of temperature data to the structural model is much more difficult and automation of the process is highly desirable. When the thermal model elements are larger than the structural model elements, the temperature distribution functions used to formulate the element conductivity matrix may be used. When the thermal model is more refined than the structural model, the structural-node temperature is approximated as a weighted average of the temperatures of the surrounding thermal nodes.

- RADIATION VIEW FACTOR CALCULATION
- SOLUTION LOGIC CAPABILITY
- THERMAL-STRUCTURAL MODEL DATA TRANSFER

Figure 13

SUMMARY

The SPAR Thermal Analyzer is a modular, interactive program for general heat-transfer analysis (fig. 14). It analyzes problems having conduction, convection, radiation and mass-transport heat transfer with time, temperature and pressure dependent properties. Steady-state temperature distributions are determined by a direct solution method for linear problems and a modified Newton-Raphson method for nonlinear problems. An explicit and several implicit methods are available for the solution of transient heat-transfer problems.

Finite-element plotting capability is available for model checkout and verification. Temperature plotting is currently not directly available. The SPAR system uses a data base for all data transfer between processors and allows recovery of almost all data and a good capability to access all data.

At the present time, the SPAR Thermal Analyzer is the main software focal point for research and technology efforts in structural heat transfer at the Langley Research Center. The SPAR Thermal Analyzer will be available through COSMIC in the near future.

SPAR THERMAL ANALYZER

- MODULAR, INTERACTIVE PROGRAM
- CONDUCTION, CONVECTION, RADIATION AND MASS-TRANSPORT HEAT TRANSFER
- STEADY STATE AND TRANSIENT ANALYSIS

  EXPLICIT AND IMPLICIT SOLUTION METHODS
- PLOTING CAPABILITY
- EXCELLENT DATA ACCESS
- WILL BE AVAILABLE FROM COSMIC
- MAIN SOFTWARE FOCAL POINT OF LaRC R & T EFFORTS IN STRUCTURAL HEAT TRANSFER

Figure 14

REFERENCES

1. Marlowe, M. B.; Moore, R. A.; and Whetstone, W. D.: SPAR Thermal Analysis Processors Reference Manual, System Level 16. NASA CR-159162, 1979.

2. Hindmarsh, A. C.: A Collection of Software for Ordinary Differential Equations. Rept. No. UCRL-82091, Jan. 1979, Lawrence Livermore Laboratory.