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# AN AUTOMATIC DATA SYSTEM FOR VIBRATION MODAL TUNING AND EVALUATION

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16. Abstract

A digitally based automatic modal tuning and analysis system developed to provide an operational capability beginning at 0.1 hertz is described. The elements of the system, which provides unique control features, maximum operator visibility, and rapid data reduction and documentation, are briefly described; and the operational flow is discussed to illustrate the full range of capabilities and the flexibility of application. The successful application of the system to a modal survey of the Skylab payload is described. Information about the Skylab test article, coincident-quadrature analysis of modal response data, orthogonality, and damping calculations is included in the appendixes. Recommendations for future application of the system are also made.

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# AN AUTOMATIC DATA SYSTEM FOR VIBRATION MODAL TUNING AND EVALUATION

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## SUMMARY

A state-of-the-art data system was developed to achieve the objectives of the vibration modal survey phase of the Skylab vibroacoustic test program. The low-frequency requirements dictated a digital-based system capable of operation from 0.1 to 100 hertz.

An automatic modal tuning and analysis system was conceived and developed to meet the stringent test requirements and to achieve the objectives of the modal survey. The system uses digital techniques to provide positive control of test conditions, a high degree of specimen safety, rapid data acquisition and reduction, and immediate documentation of modal response characteristics. Man-computer interactive control allows ample operational flexibility.

The system was sucessfully used to perform a modal survey of the Skylab payload in the launch and orbital configurations. The system incorporates analytical and experimental procedures to fully close the circle of modal survey implementation: pretest analysis, test implementation, and posttest loads analysis. Data derived during pretest analysis are an integral part of the data base available to complement and assess the data obtained experimentally during system application. The system output consists of a complete data package that may be immediately used for loads analysis without further reduction or manipulation. This technique provided the foundation for the automatic modal tuning and analysis system design criteria and contributed significantly to the success and wide acceptance of the system.

## INTRODUCTION

The NASA Lyndon B. Johnson Space Center (JSC) Vibration and Acoustic Test Facility (VATF) was built in 1964 and was equipped for performing a wide range of structural dynamic testing. Since the inception of the VATF, test operations

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have involved both acoustic and mechanical excitation of complex elastic structures inherent in manned spacecraft. In the intervening years, the facility test capabilities have been constantly refined to meet the diverse requirements of numerous Apollo spacecraft test programs. In turn, the subsequent Skylab vibroacoustic test program, recently completed at VATF, stimulated development of a high-performance system for performing vibration modal surveys.

The computer-based automatic modal tuning and analysis system (AMTAS) is a major advance in the state of the art of such systems available within NASA. The AMTAS uses a greater complexity of digital techniques to perform excitation force control and data acquisition, processing, and display than was previously available. These digital techniques eliminate the low-frequency processing limits of analog instruments and provide substantial improvements in the quality of the resulting data. The system includes a large number of automated functions to expedite test operations, to provide maximum test article safety during test operations, and to eliminate excessive test article exposure and program delays by providing rapid data acquisition and reduction capabilities.

The AMTAS has been used on two Skylab modal surveys involving the largest and most complex spacecraft built by NASA. Data were obtained from the surveys of two configurations of the Skylab orbiting laboratory, which consists of an assembly of six modules. The Skylab test article is discussed in appendix A. These configurations, both approximately 21 meters (70 feet) high, embodied complex, unsymmetrical structural arrangements that weigh approximately 54 430 kilograms (120 000 pounds). These modal surveys, which required documenting all modes in the range of 1 to 45 hertz, were performed despite severe limitations due to schedule time, number of shaker excitation points, and response measurements available. The complexity of the Skylab structure and the urgency of the survey results warranted development of the AMTAS, which is nearly as complex as the Skylab structure. Through these Skylab surveys, AMTAS concepts and capabilities were verified, and a highly mature modal survey system consisting of sophisticated test equipment and software resulted. The purpose of this paper is to present a general overview of the hardware and software components of the AMTAS. A functional description of the system capabilities also is given.

As an aid to the reader, where necessary the original units of measure have been converted to the equivalent value in the Système International d'Unités (SI). The SI units are written first, and the original units are written parenthetically thereafter.

## SYSTEM DESCRIPTION

The system description includes AMTAS general features, the computer, support subsystems, the excitation and excitation control subsystems, the data acquisition subsystem, and the monitoring subsystem.

## General Features

Digital techniques are used to provide a low-frequency operating bound of virtually zero hertz without compromise of capability. Positive excitation control is achieved through force feedback digital control of the forcing function. The narrow-band filtering and coincident-quadrature (co-quad) capabilities are extended to essentially zero hertz through software for digital filtering and data reduction.

Six elements constitute the AMTAS: a computer, a software support package, an excitation control subsystem, an excitation subsystem, a data acquisition subsystem, and a monitoring subsystem. Concise information about data storage and presentation is presented in table I. The conceptual layout of the AMTAS is shown in figure 1. Some ancillary support systems used in the application of AMTAS to perform related tasks are discussed in the latter part of this section.

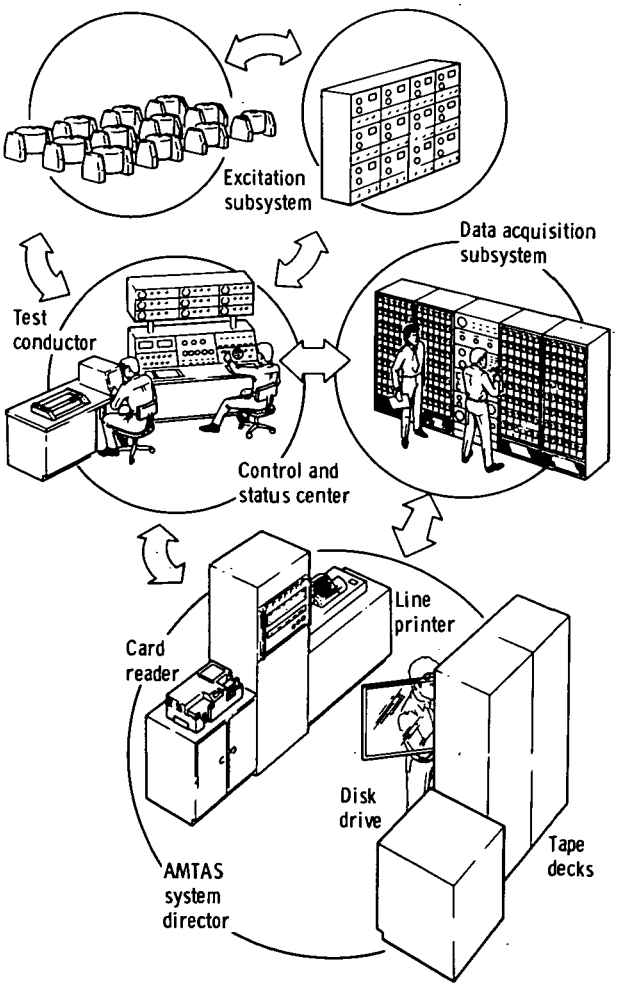


Figure 1.- Conceptual layout of AMTAS.

The control, data acquisition, and excitation subsystems are interconnected with the computer through the peripherals (fig. 2). Man-computer interactive control of system functions is provided by the keyboard display units at the control console. Real-time data reduction, modal purity, and data validity assessment results are displayed on the alphanumeric cathode-ray-tube (CRT) display. Quick-look graphic documentation is presented on the graphic CRT hard-copy unit and digital plotter.

## Computer

A general-purpose computer having 32 000 words of core memory is used to direct the system. The computer supports the following peripherals: a card reader, a card punch, a line printer, a disk drive, tape decks, a console typewriter, input signal selectors, a multiplexer (MUX) and analog-to-digital (A/D) converter, an alphanumeric CRT with keyboard, an alphanumeric-graphic CRT with keyboard, a force and acceleration detector, and digital plotters. The physical placement of the computer and the peripherals is indicated in figure 3.

TABLE I.- DATA STORAGE AND PRESENTATION MATRIX

| Operation | Presentation medium[a] | | | | | | Storage medium[a] | | |
|---|---|---|---|---|---|---|---|---|---|
| | Alphanumeric CRT | Graphic CRT and hard copy | Line printer | Digital plotter | Oscillograph | Card | Digital magnetic tape | Analog magnetic tape | Disk |
| SUPSS | 2,9,10 | N/A | 2,5,6,7,9 | 3 | N/A | N/A | 2,5,6,7 | N/A | N/A |
| SUPTS | 2,9,10 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| SUPTM | 2,9,10 | N/A | N/A | N/A | N/A | N/A | N/A | N/A | N/A |
| SUPSM | 2,9,10 | N/A | 2,5,6,7,9 | 3 | N/A | N/A | 2,5,6,7 | N/A | N/A |
| SUPMD | 2,9,10 | N/A | N/A | N/A | 1 | N/A | N/A | 1,6 | N/A |
| SUPDW | 2,9,10 | N/A | 2,5,6,7,8,9 | N/A | N/A | N/A | 2,5,6,7,8 | N/A | 2,4,5,6,7,8,9 |
| ASUPS | 9,10 | N/A | 2,9 | N/A | N/A | N/A | N/A | 1,6 | N/A |
| ORTHO | 11 | N/A | 11,12 | N/A | N/A | N/A | N/A | N/A | N/A |
| Print | N/A | N/A | 2,4,5,6,7,8,9 | N/A | N/A | N/A | N/A | N/A | N/A |
| Plot | N/A | 4 | N/A | 4 | N/A | N/A | N/A | N/A | N/A |
| Punch | N/A | N/A | N/A | N/A | N/A | 5,2 | N/A | N/A | N/A |

[a]Data legend: 1 - analog response data, 2 - coincident quadrature (co-quad), 3 - co-quad × 10 000, 4 - translated co-quad, 5 - bookkeeping data, 6 - reference force, 7 - total acceleration, 8 - phase angle, 9 - forcing distribution, 10 - high-limit acceleration, 11 - orthogonality result, 12 - 2 × 2 orthogonality matrices, and N/A - not applicable.

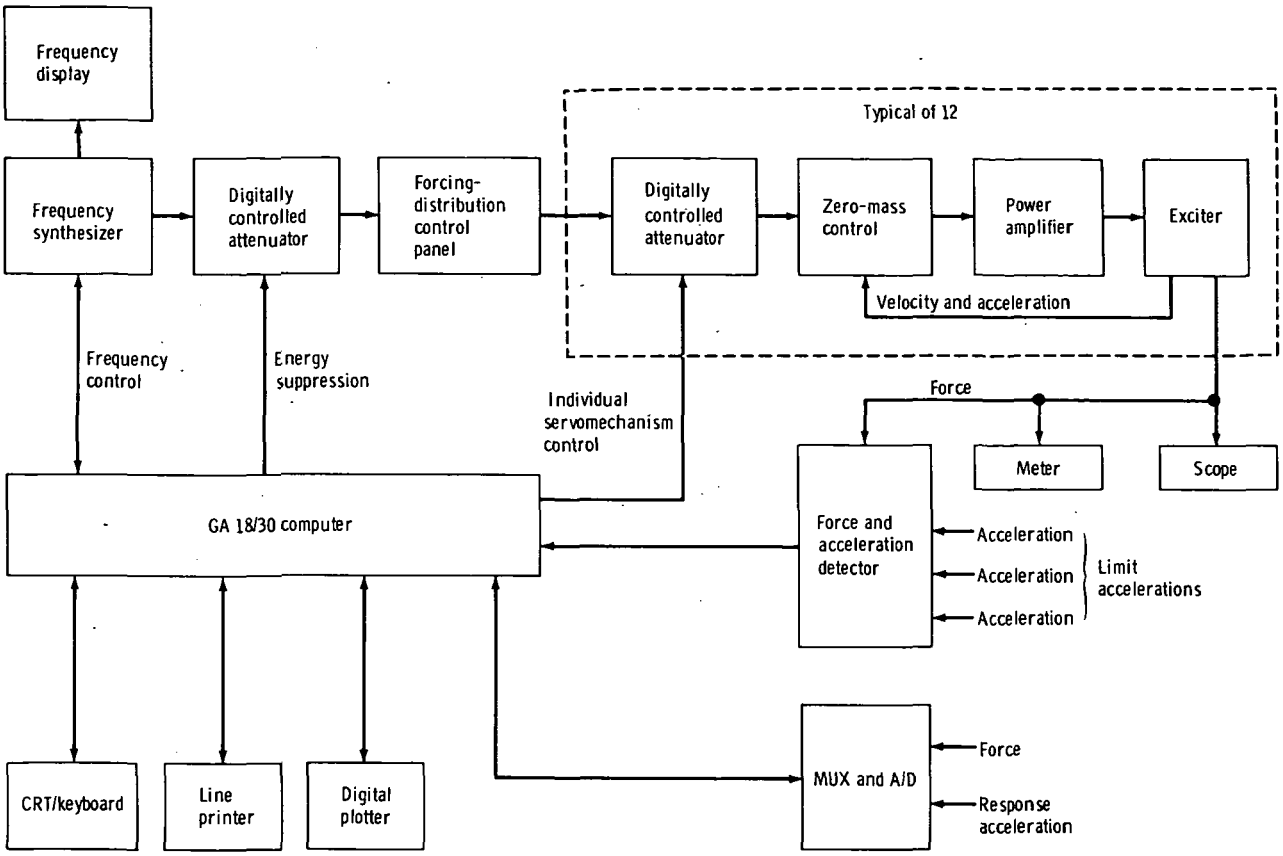


Figure 2.- Excitation control subsystem.

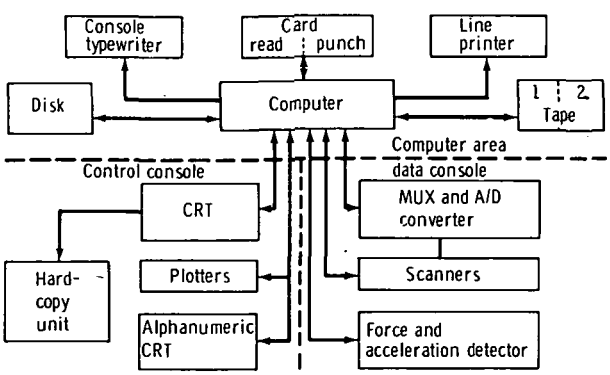


Figure 3.- System director peripherals.

The computer operates under a group of programs (supplied by the manufacturer) for generating, organizing, testing, and executing programs for real-time data acquisition and control. The major components of this software include a machine language assembler, a FORTRAN compiler, a loader, a disk utility program, a supervisor, and a real-time system director.

The system director, which controls the real-time data acquisition and control programs, consists of time-sharing control, program sequence control, master interrupt control, interval timer control, and error alert control. A subroutine library consists of programs for

input-output conversion and for performing arithmetic, functional, selective dump, debug, and miscellaneous operations. In addition, three other categories of software are required for the system: input-output handlers for nonstandard peripherals, application programs (real time and off line), and test and validation routines. These three groups of software, referred to as the software support package, were written specifically for the AMTAS application.

## Software Support Package

Five process control functions are provided by the software support package: sweep direction and linear rate, response channel selection, phase-lock control, force distribution control, and limiting of critical accelerations. Data acquisition is inhibited when any servomechanism (servo) correction (force level or frequency) is in progress. The software support package also provides the data acquisition, data reduction, and modal documentation features of the system.

A modular structure for the software support package is dictated by several realities of test performance. Core memory limitations are greatly diminished by the use of overlay and disk-resident structured coreloads that are loaded on demand. Subroutines are used to the greatest possible extent, and many are reentrant. File data must be installed early (with final corrections expected before the survey commences) to enable performance of the system confidence test. These files (e.g., the mass model of the structure) are sometimes corrected during the course of the test. These requirements are accommodated by separate data files in the software support package. The organization of the software support package is shown in figure 4.

All structure-dependent data exist in files that are easily maintained during model updates and revisions. The operational program, the file creation program, and the file input program with data modules are stored and maintained separately. For a future modal test, only the file input modules need be revised to include the structure-peculiar data; other modules are independent of structure.

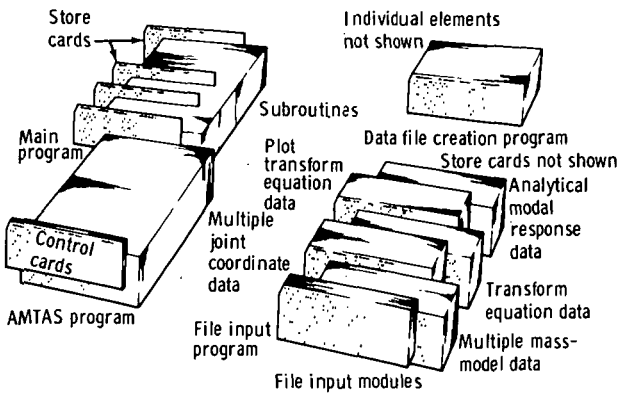


Figure 4.- Organization of software support package.

The data file creation module creates the files required for program execution, including the structure-dependent data. The structure-dependent data files can be revised at any time without disturbing the other programs by replacing the data deck and reloading and executing the file input program.

Process control.- The process control sequence during modal sweeps is shown in figure 5. The sweep parameters and reference transducers are selected by keyboard entry. Frequency incrementing is initiated by command. The individual force distribution and

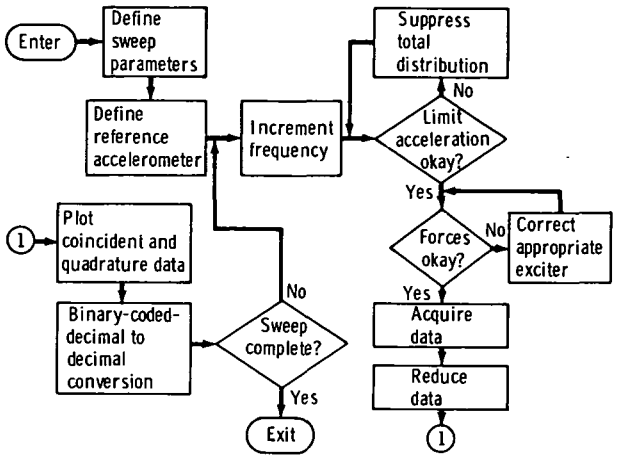


Figure 5.- Process control, sweep mode.

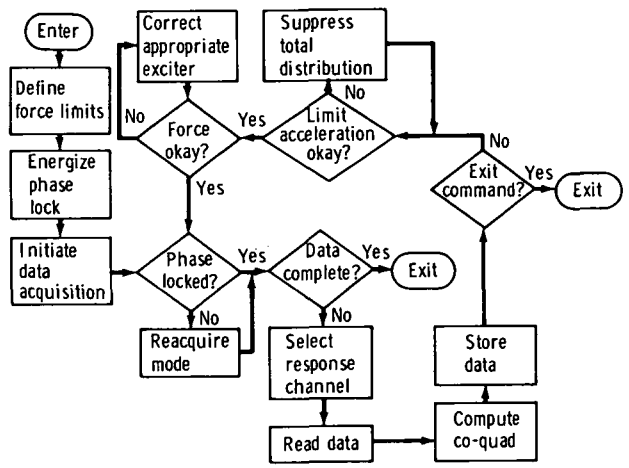


Figure 6.- Process control, dwell mode.

limit accelerations are checked and corrected if required. Data samples are acquired, and total-response data from three reference accelerometers are resolved into co-quad components. The co-quad data are plotted, and the frequency is incremented. This sequence is repeated until the sweep is completed.

The process control sequence during a modal dwell is shown in figure 6. After the modal decay indicates that the desired mode has been separated from adjacent modes, the run number and the mode number are entered on the CRT keyboard. All other bookkeeping and test data are acquired by the computer to completely eliminate manual recording errors. Phase lock and data acquisition are initiated by keyboard entry. The first set of three response channels is selected for co-quad analysis. When data sampling is complete, the next set of response accelerometers is selected for priority level sampling, while data reduction, documentation, and storage continue on the main-line level of software operation. If an exit command has not been entered on the keyboard, the force distribution and limit acceleration are corrected, if required. The sequence is repeated until all response data are acquired or until an exit command is received. Fourteen digital servos are active during the modal dwell: twelve individual force servos, the total energy servo, and the frequency servo (phase lock).

Data acquisition.- Several data acquisition functions are common to both sweep and dwell modes of operation. Bookkeeping data (run number and mode number) are entered by means of the manual CRT keyboard, shown at the left of figure 2. The format is printed out on the display such that the letter "X" appears where data must be entered by the operator. After data entry, the send key is depressed to initiate read in by the computer. The format is updated and the input stored on disk. The run and mode numbers are used to subscript the incoming data for proper organization and storage in disk and tape files.

A view of the control console is given in figure 7. The keyboard display units are shown on the right side of the control console. Overall views of the AMTAS are shown in figures 8 and 9.

Figure 7.- The AMTAS control console.

Figure 8.- Overview of AMTAS looking toward the shaker amplifier console.

Figure 9.- Overview of AMTAS looking toward the narrow-band filters.

The force level of each active exciter is displayed on the alphanumeric CRT. Limit acceleration status is displayed at the bottom of the CRT at each force-level update time.

Response data are acquired by a keyboard-selected load cell and a set of three accelerometers. These transducers are fixed throughout a sweep. However, in the tuning mode, the load cell and the response accelerometers may be selected or changed at any time to examine response characteristics of the structure as the forcing distribution and frequency are varied to optimize a desired mode. In the dwell mode, the reference load cell is selected by keyboard entry. The data acquisition sequence, initiated on the keyboard, consists of acquiring response data from all accelerometers (maximum of 200) in groups of 3.

Data reduction.- The software support package provides maximum real-time visibility and immediate posttest documentation within minutes after response data from all transducers are acquired. This result is achieved by maximizing the data reduction that is performed as the data from each transducer are acquired.

The raw voltage data are converted to engineering unit data, and any direct-current component introduced by the signal-conditioning equipment is eliminated. These converted data are then processed by a Fourier analysis routine to digitally filter the data and to obtain the real and imaginary Fourier coefficients required for co-quad component resolution. Co-quad reduction techniques are described in appendix B. The co-quad components are derived and stored in core and magnetic tape files. These co-quad data are normalized to input force to remove this dependence.

After all data are acquired and reduced to co-quad components, the normalized quadrature data are translated to the mass-model (generalized) coordinates, and the generalized mass is computed. The generalized quadrature deflections are then normalized to unity generalized mass. These normalized, generalized quadrature deflection data are used for all data documentation.

Data documentation.- Documentation (fig. 10) consists of co-quad plots, decay curves, listing of raw voltage, engineering unit and generalized coordinate data, orthogonality matrix printout, modal plots, and a punched-card deck of modal response data. This documentation is available immediately after modal acquisition is completed.

The CRT display unit affords a dynamic, real-time status display. Parameters included are force levels, frequency, error, and status messages. Subroutine execution is initiated by a command entered on the keyboard.

Data listing by the line printer is initiated by keyboard entry. This listing is available for single modes or a total set of modes and includes status and bookkeeping, raw voltage, and engineering unit and generalized coordinate (normal mode) data. An additional keyboard entry will result in an orthogonality printout.

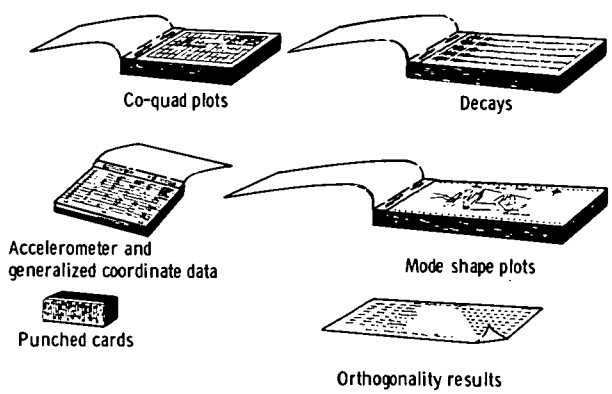


Figure 10.- Modal documentation.

Modal deflections for a given mode can be produced in the form of cards by means of a nonprocess program in an off-line, time-share computer mode. A set of stick plots (15 maximum) documents a mode in the form of node deflections as functions of vehicle station.

## Excitation Control Subsystem

The use of digital feedback force-control techniques avoids the need for constant-bandwidth tracking analyzers and an analog servo unit, either of which imposes a low-frequency limit on the system. The frequency synthesizer, controlled by the computer (fig. 2), provides the desired frequency. The finest resolution

is 0.01 hertz. The system master gain, which controls the total forcing distribution, is manually initialized but is adjusted under direct program control to suppress the total energy supplied to the structure if critical acceleration levels are exceeded. The signal from the ensemble of critical-location sensors, which sense the highest signal level, is selected with a force and acceleration detector. The output of this unit is fed to the computer to control the total energy level.

The forcing distribution is manually programed by level set and phase selection for each individual exciter. Phase adjustment is by sense only (0° or 180°). Other phase manipulation is undesirable because normal mode motions and damping forces act, respectively, in a 0° or 180° sense. The driving forces are continuously variable to cancel the internal damping shears and moments and thus to preserve the steady-state natural mode. To ensure preservation of the forcing distribution and natural mode, a detected signal from each amplifier representing force is monitored by the computer to allow computer adjustment of the current supplied to each individual exciter. If the system total amplitude is corrected by the computer, the individual forcing-distribution digital control output is factored to prevent recompensation.

A separate component of the excitation control subsystem is the zero-mass control. This unit eliminates the effects of armature and mechanical force-input coupler (stinger) mass during modal decays or when a zero-drive signal is applied to the exciter. In addition, because the armature circuit remains active during a modal decay, the unit must compensate for back electromotive force generated by the moving coil. A secondary effect of the control unit is to transform a voltage amplifier into an approximation of a current amplifier. A velocity transducer measures the differential velocity between the exciter body and the armature. (Back electromotive force is directly proportional to the differential velocity.) Mass cancellation is directly proportional to the acceleration of the armature-stinger assembly. Therefore, use of the acceleration signal measured on the vehicle at the stinger interface is appropriate. The signals generated by the two transducers are correctly phased and summed with the excitation drive signal, if present, to produce a positive-feedback system. The feedback signal is summed with the drive signal instead of switching the feedback signal into the amplifier input circuit on initiating a decay.

## Excitation Subsystem

A single channel of the excitation subsystem consists of a solid-state, direct-coupled power amplifier; a field supply and control unit; a low-frequency, long-stroke exciter assembly; and a stinger. A maximum of 12 channels can be excited simultaneously by using a combination of 16 power amplifiers/field supplies and 24 exciters. A patching network provides access from a given exciter to any power amplifier.

The primary consideration in the design of the excitation system is to ensure that no phase shift occurs between any of the inputs to the structure. Phase shifts may occur electrically in the input circuitry to the power amplifiers or within the power amplifiers. A phase shift can also occur mechanically in the shaker support structure or the stinger. Direct coupling is advantageous in minimizing

or deleting phase shifts in the input and drive circuits and is necessary for very-low-frequency operation. Direct coupling is used in the system principally because of the low-frequency design criterion.

The stinger assemblies were designed to be stiff enough to transmit the force input without the occurrence of an appreciable phase shift (less than 5°) at frequencies as high as the upper frequency limit. Nominal guidelines are to have the first mode of the stinger, axial or bending, at a minimum frequency of three times the upper frequency limit of the test band.

## Data Acquisition Subsystem

A diagram of the data acquisition subsystem is shown in figure 11. The analog front end of the subsystem includes the following systems.

1. A strain gage signal-conditioning system capable of being patched into the test laboratory junction boxes supplies power, signal amplification, calibration capability, and bridge balancing capability for one to four active-element strain gage circuits and strain gage transducers, such as load cells.

2. A servo accelerometer signal-conditioning system capable of being patched into the test laboratory junction boxes supplies power, output signal balancing, and calibration for sensitive servo-type acceleration transducers.

The analog front end conditions the acceleration and force signals. Groups of transducers are selected automatically by the computer as inputs to the low-pass antialiasing filters. Digitized samples of the inputs are acquired by an MUX and A/D converter. Fourier analysis of these digitized data provides complex Fourier transform coefficients for the computation of coincident and quadrature values.

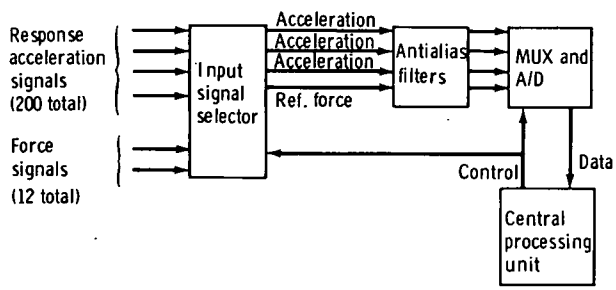


Figure 11.- Data acquisition subsystem.

## Monitoring Subsystem

The peripheral monitoring subsystem consists of a group of analog meters, analyzers, and display units that aid tuning operations and provide continuous verification of system operation. The function of the monitoring subsystem is to display 12 Lissajous patterns simultaneously to aid the operator in tuning.

Twelve dual-channel dynamic analyzers act as narrow-band filters (5 hertz) to provide high-quality output signals of force and acceleration to the display units. In addition, a 90° phase shift is introduced between the two channels of the analyzer so that the Lissajous figure at resonance is a straight line rather than an ellipse. The paired outputs of the analyzers are hard wired to signal multiplexing units and then to bistable storage display units, which display four patterns on a single

unit. (Storage display units are superior to standard oscilloscopes when operating at frequencies of less than 5 hertz.) Two options are available to the operators for tuning at frequencies of less than 3 hertz, where the analyzers cannot function. Because response signals are of much higher quality at lower frequencies, the main function of the analyzers is to provide the 90° phase shift between the force and acceleration signals. Therefore, the raw acceleration can be used to tune on elliptical patterns. An alternative is to use the raw velocity signal available from the shaker-mounted velocity transducers. By using these transducers only at the very-low frequencies, the phase problems associated with shaker body motion are avoided.

Other features of the monitoring subsystem include miniature oscilloscopes for continuous display of the raw force wave shape and analog voltmeters connected through a signal selector from the analyzer outputs. The analog meters are used to monitor force and acceleration when the central processor is not on line and to cross-check the digital data acquisition system during dwell operations by comparing analog and digital readings.

## Ancillary Support Systems

The soft-spring suspension system provides a simulated free-free environment in which to excite and measure the natural elastic vibration modes of a structure. A maximum of 16 units can be used to suspend the test article. Each unit can support as much as 22 700 kilograms (50 000 pounds) while maintaining a very low resonance frequency.

The closed-circuit television capability consists of eight video channels, including cameras and controls. The video control console permits adjusting the position of each camera image. Patch panel and pushbutton selection capability are available for matching cameras and monitors. Scan conversion, split-screen special effects, waveform monitoring, and video signal conditioning are also available.

Analog data recording systems include the following:

1. Analog magnetic tape recorders having frequency multiplex input capability are used to record data for off-line co-quad reduction.

2. Oscillograph chart recorders that include dry-development, light-sensitive papers for recording galvanometer deflections are used to acquire unfiltered accelerometer data during modal decays.

An off-line co-quad analysis capability was developed to process data acquired from many transducers during an incremental sinusoidal sweep over a wide frequency band. The wide-band sweep is performed to define the structural modes. The processed data are used in conjunction with the analytical data to define target modes and to predict optimum forcing distributions.

# SYSTEM APPLICATION

Two keyboard CRT terminals are used for entering test parameters, initiating commands to the software system, and displaying data and computations. When the computer is brought on line to support AMTAS operations, the system controller format (fig. 12) is displayed on the alphanumeric CRT. Several key features are programed into the display. As shown in the controller format, the correct page of the operating procedure that applies to the operation in progress is displayed, the allowed options are defined, and instructions for entering these options are given to the operator. The general scheme is to present the system operating instructions as follows.

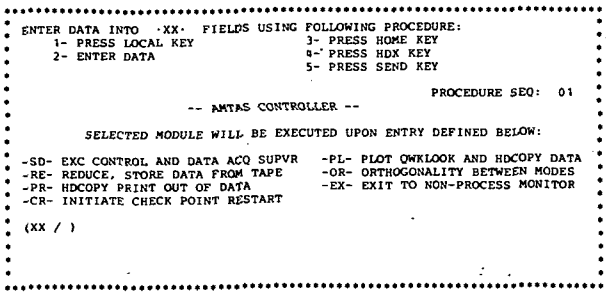


Figure 12.- System controller CRT display.

1. Alphanumeric CRT

a. Line 1 consists of messages pertaining to general system operation and required entries (to be exercised by AMTAS control). Error messages are also displayed on this line.

b. Lines 2 to 19 are used for definition of allowed entries. (During real-time operations, this area is used for display of dynamic test parameters and the definitions are presented on the graphic CRT display.)

c. Line 20 consists of messages pertaining to vibration control (initializing gains, phases and level, etc.).

2. Graphic CRT

a. The storage area is used for definition of allowed entries when the alphanumeric CRT is displaying test parameters.

b. The scratch pad area is used to enter option messages. (The alphanumeric keyboard cannot be used when test parameters are being continuously updated.)

This scheme ensures that the correct operation is performed at the proper time so that manual functions are performed synchronously with programed operations. Operator directions and error messages (lines 1 and 20 of the alphanumeric CRT) are blinked on and off to capture the operator's attention.

The system controller provides a logic procedure (fig. 13) for selecting the basic options for tuning and acquiring data for a mode or manipulating and displaying modal response data for assessing the purity and validity of a previously acquired mode. In the following paragraphs, the options are discussed in the nominal operational sequence.

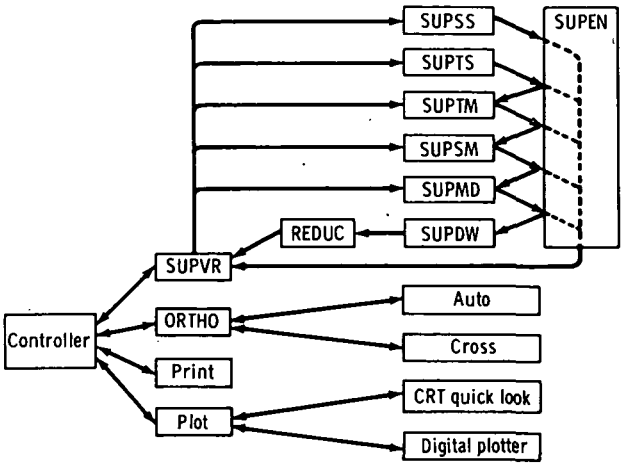


Figure 13.- Application software logic.

```
ENTER 'C' ON TEK KBD TO CONTINUE S/W SEQUENCE

AMTAS INITIALIZATION PROCEDURE:                    PROCEDURE SEQ:  01

1- PATCH LIMIT ACCELS                  7- SUMDET IN COMPUTER MODE
2- NORMALIZE WEIGHTING AMPLIFIERS      8- MASTER GAIN FULL CCW
3- PATCH INPUTS TO SUMDET              9- INDIV GAINS FULL CCW
4- PATCH SCOPE AND METER PANELS        10-PHASE CONTROLS TO OFF
5- READY DIGITAL PLOTTER               11-ZERO MASS ENABLED
6- SYNCON IN REMOTE MODE               12-MAG. TAPES INITIALIZED


                S/W HOLD-PERFORM LISTED OPERATIONS
```

Figure 14.- The AMTAS initialization procedure CRT display.

```
ENTER DATA INTO (XX) FIELDS USING FOLLOWING PROCEDURE:
    1- PRESS LOCAL KEY              3- PRESS HOME KEY
    2- ENTER DATA                   4- PRESS HDX KEY
                                    5- PRESS SEND KEY


CH 00 LOC (XXX )  G=(+X.XXE+XX )    CH 01 LOC (XXX )  G=(+X.XXE+XX )
CH 02 LOC (XXX )  G=(+X.XXE+XX )    CH 03 LOC (XXX )  G=(+X.XXE+XX )
CH 04 LOC (XXX )  G=(+X.XXE+XX )    CH 05 LOC (XXX )  G=(+X.XXE+XX )
CH 06 LOC (XXX )  G=(+X.XXE+XX )    CH 07 LOC (XXX )  G=(+X.XXE+XX )
CH 08 LOC (XXX )  G=(+X.XXE+XX )    CH 09 LOC (XXX )  G=(+X.XXE+XX )
CH 10 LOC (XXX )  G=(+X.XXE+XX )    CH 11 LOC (XXX )  G=(+X.XXE+XX )
CH 12 LOC (XXX )  G=(+X.XXE+XX )    CH 13 LOC (XXX )  G=(+X.XXE+XX )
CH 14 LOC (XXX )  G=(+X.XXE+XX )    CH 15 LOC (XXX )  G=(+X.XXE+XX )
CH 16 LOC (XXX )  G=(+X.XXE+XX )    CH 17 LOC (XXX )  G=(+X.XXE+XX )
CH 18 LOC (XXX )  G=(+X.XXE+XX )    CH 19 LOC (XXX )  G=(+X.XXE+XX )
CH 20 LOC (XXX )  G=(+X.XXE+XX )    CH 21 LOC (XXX )  G=(+X.XXE+XX )
CH 22 LOC (XXX )  G=(+X.XXE+XX )    CH 23 LOC (XXX )  G=(+X.XXE+XX )
          LIMIT ACCEL F.S. A/D COUNT=(+X.XXXE+XX / ) VOLTS
```

Figure 15.- Patch correspondence table CRT display.

## Supervisor Option

The excitation control and data acquisition supervisor option (SUPVR) is composed of the software modules for system initialization, modal tuning, and data acquisition. All excitation, real-time monitoring and control, and data acquisition are performed with this supervisor. The remaining options of the controller are associated with data analysis, display, and assessment. The initialization procedure (fig. 14) is displayed immediately after the supervisor is selected. After the initialization is completed, the patch correspondence table (fig. 15) is displayed. Completion of this table is necessary to select 24 limit accelerometers from the 200 total-response accelerometers. After this table is completed, the supervisor options are displayed (fig. 16). Eight operational possibilities are available within the supervisor.

1. The SUPSS option consists of a single-shaker, wide-band sinusoidal sweep with digital data acquisition. Three accelerometers can be selected for generating co-quad plots (fig. 17) on the digital plotter during one sweep. The raw co-quad data are stored on magnetic tape and listed on the line printer.

```
TO CONTINUE S/W SEQUENCE:
   1- DO NOT MOVE CURSOR
   2- ENTER APPROPRIATE CHARACTERS
   3- HOLD CTRL KEY DOWN, PRESS 'ETX' KEY
   4- PRESS SEND KEY
ENTRIES DEFINED BELOW ARE ALLOWED:
   SS- SWEEP SINGLE /DIGITAL DATA ACQ/
   AS- SWEEP SINGLE /ANALOG DATA ACQ/
   TS- TUNE SINGLE
   TM- TUNE MULTIPLE
   SM- SWEEP MULTIPLE
   MD- MODAL DECAY
   DW- MODAL DWELL
   RT- RETURN TO AMTAS
```

Figure 16.- Operation selection table CRT display.

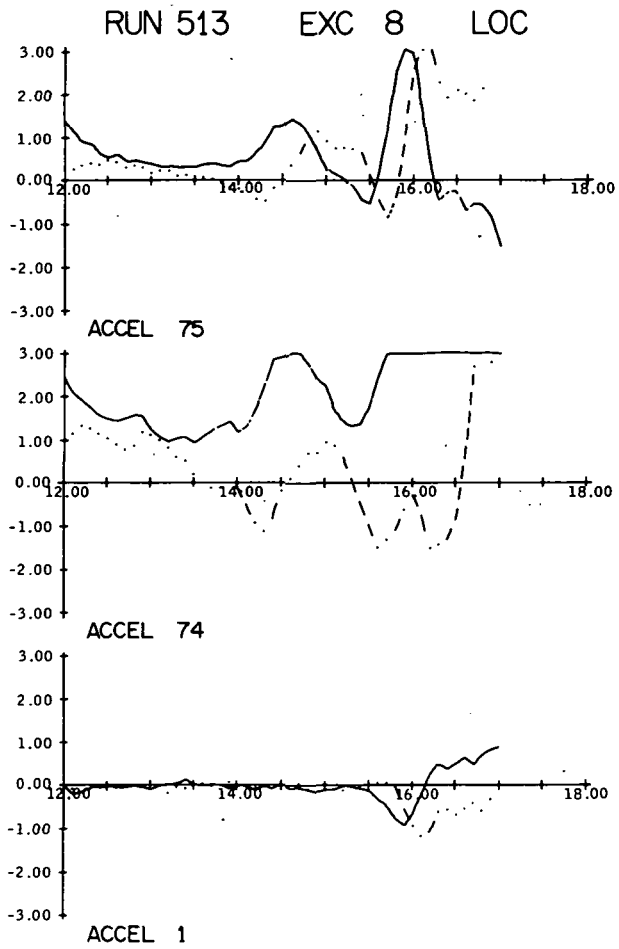


Figure 17.- Portion of wide-band sweep co-quad plot.

2. The ASUPS option consists of a single-shaker, wide-band sinusoidal sweep with analog data acquisition for off-line co-quad reduction (not shown in fig. 13). Typical data reduced with the off-line software are given in figure 18.

3. The SUPTS option consists of tuning operations with a single shaker for approximate frequency settings.

4. The SUPTM option consists of tuning operations with multiple shakers (maximum of 12). Fine tuning is accomplished with this software module. The alphanumeric CRT display of test parameters, similar to those displayed for other supervisor options, is given in figure 19. Appropriate entries for this option are shown in figure 20. The line-printer listing of the sequence log obtained during a tune multiple (SUPTM) operation is shown as run 642 in figure 21. This listing is similar to sequence-log data obtained during SUPSS, ASUPS, and SUPTS operations.

5. The SUPSM option consists of a multiple-shaker, narrow-band sinusoidal sweep to define the resonance condition. Three accelerometers can be selected for generating co-quad plots on the digital plotter during one sweep. The raw co-quad data are stored on magnetic tape and listed on the line printer. Plots similar to those shown in figure 18 result from this operation.

6. The SUPMD option consists of modal decay with signals from a maximum of 24 selected accelerometers recorded on an oscillograph. Sequence-log output from this operation is shown in figure 21 (runs 643 and 644).

7. The SUPDW option consists of modal dwell operation for digital data acquisition in coincident and quadrature format. The system director checks the phase lock, if in use, and the force distribution status while selecting input signals and resolving the data into coincident and quadrature components. The data are stored on magnetic tape, displayed on the CRT, listed on the line printer, and transferred to cards as a backup data file. A portion of the sequence log generated during an SUPDW operation is shown in figure 21 (run 645).

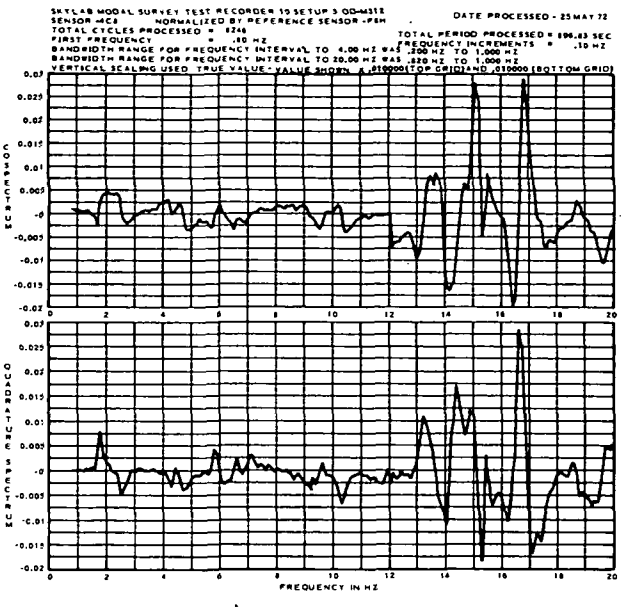


Figure 18.- Off-line co-quad reduction: typical plots of coincident and quadrature components of total acceleration. Top: coincident component (normalized to reference force); bottom: quadrature component (normalized to reference force).

```
ENTER DESIRED OPTION ON TEK KBD TO CONTINUE S/W SEQUENCE
TM OPERATION     RUN (XXX )  FREQ: +X.XXXX+XX HZ.  PROCEDURE SEQ:  08
SWP--ST: (+X.XXE+XX )
C/Q ACCELS---(XXX ) CO:+D.DD+DD   (XXX ) CO:+D.DD+DD   (XXX ) CO:+D.DD+DD
 BW= +X.XX+XX      QUAD:+D.DD+DD        QUAD:+D.DD+DD        QUAD:+D.DD+DD
 REF CH=(XX)      RATIO:+D.DD+DD       RATIO:+D.DD+DD       RATIO:+D.DD+DD
 CH 01       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 02       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 03       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 04       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 05       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 06       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 07       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 08       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 09       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 10       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 11       LOC:(XXX )       SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
 CH 12       LOC:(XXX / )     SET #= +E.EE+EE     ACTUAL #= +F.FF+FF  PH J
HI LIMIT ACCEL--LOC: GGG    LEVEL:+H.HH+HH G     .XX OF LIMIT VALUE
   ADJUST FORCING DIST AND FREQ AS REQD TO OPTIMIZE MODAL RESPONSE
```

Figure 19.- Modal tuning (SUPTM) format CRT display.

```
TO CONTINUE S/W SEQUENCE:
   1- DO NOT MOVE CURSOR
   2- ENTER APPROPRIATE CHARACTERS
   3- HOLD CTRL KEY DOWN. PRESS 'ETX' KEY
   4- PRESS SEND KEY
ENTRIES DEFINED BELOW ARE ALLOWED:
   CO- COMPUTE-CO/QUAD
   ST- STOP OPERATION
   FRBSXXX -DELTA FREQ IN +/- .01 INCR. AND COMPUTE CO/QUAD
   PR- PROCEED TO NEXT OPERATION
   AFCCCBDDDBEEEBFF - NEW ACCELS AND FG
       CCC- NEW ACCEL, POS 1, FOR C/Q ANAL
       DDD- NEW ACCEL, POS 2, FOR C/Q ANAL
       EEE- NEW ACCEL, POS 3, FOR C/Q ANAL
       FF-  NEW REF FG FOR CO/QUAD ANAL
       D-   DENOTES REQUIRED BLANK
   HI- RAPID UPDATE
   LO- NORMAL UPDATE---ONLY ENTRY ALLOWED WHEN IN 'HI' UPDATE MODE
```

Figure 20.- The CRT display of modal tuning options.

8. In the REDUC option, following the completion of the SUPDW operation (assuming that no exit entry was received during the operation), the logic flows automatically into the reduction module to prevent loss of these data caused by an inadvertent entry. In this module, all remaining data reduction is performed without any operator intervention or direction required. These reduction operations consist of translation of data to generalized coordinates, computation of generalized mass, and normalization of generalized quadrature data to unity generalized mass. The reduced data are automatically stored in the correct primary disk storage area and backup magnetic tape file area.

The "return to controller" function provides the initial display on the CRT and awaits a selection by the operator (not shown in fig. 13).

```
175/ 3/10/ 6                AMTAS COLDSTART INITIATED

175/ 3/10/33                AMTAS INITIALIZATION COMPLETE

175/ 3/10/55                MD OPERATION SELECTED

175/ 3/14/44     RUN 642    TM OPERATION COMPLETED

                            FREQUENCY = 16.20 HZ.

                            ACCEL-          - 31-          -  2-          -117-
                               CO-      -0.197584E-03   -0.874546E-05   -0.164480E-04
                             QUAD-      -0.113400E-03   -0.620806E-05    0.857374E-04
                            RATIO-       0.174236E 01    0.140872E 01   -0.191841E 00

                            REF FG  6          ANALYSIS B/W   0.95

                            FORCING DISTRIBUTION

                            EX  1      LOC  13      SET LBS =    2.17      PHASE  0
                            EX  2      LOC  14      SET LBS =    2.17      PHASE  0
                            EX  3      LOC  18      SET LBS =    1.08      PHASE  0
                            EX  4      LOC   4      SET LBS =    2.17      PHASE  0
                            EX  5      LOC   5      SET LBS =    0.00      PHASE  0
                            EX  6      LOC   6      SET LBS =   73.84      PHASE  +
                            EX  7      LOC   7      SET LBS =  142.25      PHASE  -
                            EX  8      LOC   8      SET LBS =    0.00      PHASE  0
                            EX  9      LOC   9      SET LBS =    0.00      PHASE  0
                            EX 10      LOC  10      SET LBS =    1.08      PHASE  0
                            EX 11      LOC  17      SET LBS =    1.08      PHASE  0
                            EX 12      LOC  12      SET LBS =  117.27      PHASE  -

175/ 3/20/43     RUN 643    MODAL DECAY INITIATED

175/ 3/24/14     RUN 644    MODAL EXCITATION REINSTATED

175/ 3/25/15     RUN 644    MODAL DECAY INITIATED

175/ 3/27/42     RUN 645    MODAL EXCITATION REINSTATED

175/ 3/27/59     RUN 645    DW OPERATION STARTED---MODE     25
                                  LOC       CO            QUAD          FORCE          TOTAC
                                    1    -0.844E-04    -0.536E-04    0.748E 02     0.749E-02
                                    2    -0.967E-05    -0.213E-04    0.748E 02     0.175E-02
                                    3     0.839E-04    -0.214E-04    0.748E 02     0.649E-02
                                    4     0.126E-05    -0.213E-04    0.749E 02     0.160E-02
                                    5    -0.222E-04     0.640E-05    0.749E 02     0.173E-02
                                    6     0.102E-04     0.448E-04    0.749E 02     0.344E-02
```

Figure 21.- Portion of sequence log.

## Print Option

The print option entry from the controller provides for additional printing of the generalized coordinate data from the disk unit to the line printer. Any mode previously stored on disk can be printed. Three pages excerpted from a total printout are presented in figures 22(a) to 22(c). All bookkeeping data required to define the frequency and forcing distribution are presented in figure 22(a). The format used to document the response data in accelerometer coordinates is shown in figure 22(b). The response data in generalized coordinates are given in figure 22(c).

MODE- 25
PAGE- 1

SKYLAB MODAL SURVEY ORBITAL CONFIGURATION

MODE 25 RUN 645 DAY 175 HR 3 MIN 27 SEC 59

PERIOD 0.617284E-01 SEC. FREQUENCY 16.200 HZ.

REFERENCE FORCE EXCITER 6

| EXCITER | LOCATION | PHASE(REL) | FORCE(LBS) |
|---|---|---|---|
| 1 | 13 | 0 | 2.171 |
| 2 | 14 | 0 | 2.171 |
| 3 | 18 | 0 | 1.085 |
| 4 | 4 | 0 | 2.171 |
| 5 | 5 | 0 | 0.000 |
| 6 | 6 | + | 73.840 |
| 7 | 7 | - | 142.250 |
| 8 | 8 | 0 | 0.000 |
| 9 | 9 | 0 | 0.000 |
| 10 | 10 | 0 | 1.085 |
| 11 | 17 | 0 | 1.085 |
| 12 | 12 | - | 117.275 |

GENERALIZED MASS 0.504447E-05

(a) Housekeeping data.

Figure 22.- Typical modal data summary.

| LOCATION | ID | CO (G/LB) | QUAD (G/LB) | RATIO | PHASE ANGLE (DEG) | TOTAL ACCEL. (G) |
|---|---|---|---|---|---|---|
| 1 | 427-426X | -0.8447E-04 | -0.5365E-04 | 0.1574E 01 | 32.42 | 0.7494E-02 |
| 2 | 428-426Y | -0.9672E-05 | -0.2132E-04 | 0.4535E 00 | 65.60 | 0.1754E-02 |
| 3 | 789-426Z | 0.8397E-04 | -0.2143E-04 | -0.3916E 01 | 165.67 | 0.6490E-02 |
| 4 | 430-426X | 0.1269E-05 | -0.2137E-04 | -0.5939E-01 | 93.39 | 0.1603E-02 |
| 5 | 788-426Y | -0.2222E-04 | 0.6406E-05 | -0.3469E 01 | 163.92 | 0.1732E-02 |
| 6 | 432-426X | 0.1025E-04 | 0.4483E-04 | 0.2286E 00 | 77.12 | 0.3445E-02 |
| 7 | 439-602X | -0.6942E-04 | -0.4221E-04 | 0.1644E 01 | 31.30 | 0.6073E-02 |
| 8 | 440-602Y | 0.5228E-06 | -0.4483E-04 | -0.1166E-01 | 90.66 | 0.3351E-02 |
| 9 | 443-602Z | -0.5373E-04 | -0.4101E-05 | 0.1310E 02 | 4.36 | 0.4028E-02 |
| 10 | 442-602X | 0.6597E-05 | -0.1340E-04 | -0.4921E 00 | 116.20 | 0.1116E-02 |
| 11 | 793-602Y | -0.1940E-04 | 0.2513E-04 | -0.7718E 00 | 127.66 | 0.2372E-02 |
| 12 | 444-601X | 0.3343E-04 | 0.3655E-04 | 0.9147E 00 | 47.55 | 0.3700E-02 |
| 13 | 445-602X | -0.1098E-04 | 0.3689E-05 | -0.2978E 01 | 161.43 | 0.8658E-03 |
| 14 | 446-602Y | -0.2971E-05 | -0.2431E-04 | 0.1222E 00 | 83.03 | 0.1830E-02 |
| 15 | 449-602Z | 0.9323E-05 | 0.1953E-04 | 0.4771E 00 | 64.49 | 0.1617E-02 |
| 16 | 448-602X | 0.7421E-05 | -0.2183E-05 | -0.3398E 01 | 163.60 | 0.5776E-03 |
| 17 | 794-601Y | -0.9456E-05 | 0.3739E-04 | -0.2528E 00 | 104.19 | 0.2880E-02 |
| 18 | 450-601X | -0.4292E-04 | -0.3409E-04 | 0.1258E 01 | 38.46 | 0.4092E-02 |
| 19 | 468-509X | 0.8118E-04 | 0.5229E-04 | 0.1552E 01 | 32.78 | 0.7173E-02 |
| 20 | 467-509Y | -0.2444E-04 | -0.3622E-04 | 0.6749E 00 | 55.98 | 0.3246E-02 |
| 21 | 465-509Z | -0.3525E-05 | 0.3702E-04 | -0.9520E-01 | 95.43 | 0.2762E-02 |
| 22 | 474-509X | -0.9403E-04 | 0.1353E-04 | -0.6948E 01 | 171.81 | 0.7061E-02 |
| 23 | 473-509Y | -0.9890E-04 | 0.5342E-04 | -0.1851E 01 | 151.62 | 0.8355E-02 |
| 24 | 471-509Z | -0.2043E-03 | 0.8176E-04 | -0.2498E 01 | 158.18 | 0.1635E-01 |
| 25 | 480-509X | -0.6726E-04 | -0.1025E-03 | 0.6561E 00 | 56.72 | 0.9122E-02 |
| 26 | 479-509Y | -0.8163E-04 | -0.4754E-04 | 0.1717E 01 | 30.21 | 0.7028E-02 |
| 27 | 477-509Z | -0.1769E-03 | -0.8392E-04 | 0.2108E 01 | 25.37 | 0.1457E-01 |
| 28 | 486-509X | 0.1968E-03 | 0.1122E-03 | 0.1752E 01 | 29.70 | 0.1683E-01 |
| 29 | 485-509Y | -0.9424E-05 | 0.1077E-03 | -0.8746E-01 | 94.99 | 0.8034E-02 |
| 30 | 483-509Z | 0.7245E-04 | 0.7113E-04 | 0.1018E 01 | 44.47 | 0.7543E-02 |
| 31 | 492-509X | -0.1681E-03 | -0.1299E-03 | 0.1294E 01 | 37.69 | 0.1577E-01 |
| 32 | 491-509Y | -0.8458E-04 | -0.7199E-04 | 0.1174E 01 | 40.40 | 0.8244E-02 |
| 33 | 489-509Z | -0.6427E-04 | -0.9301E-04 | 0.6910E 00 | 55.35 | 0.8391E-02 |
| 34 | 498-509X | -0.7677E-04 | -0.1162E-04 | 0.6605E 01 | 8.60 | 0.5749E-02 |
| 35 | 497-509Y | -0.1387E-04 | 0.1299E-04 | -0.1067E 01 | 136.87 | 0.1407E-02 |
| 36 | 495-509Z | 0.1120E-03 | 0.8861E-04 | 0.1264E 01 | 38.34 | 0.1057E-01 |
| 37 | 770-509X | 0.2546E-04 | -0.3152E-05 | -0.8077E 01 | 172.94 | 0.1903E-02 |
| 38 | 771-509Y | 0.4462E-04 | 0.2943E-04 | 0.1516E 01 | 33.40 | 0.3966E-02 |
| 39 | 772-509Z | -0.1113E-03 | -0.7089E-04 | 0.1570E 01 | 32.48 | 0.9792E-02 |
| 40 | 773-509X | -0.7189E-05 | -0.3411E-04 | 0.2107E 00 | 78.09 | 0.2588E-02 |

(b) Accelerometer response data.

Figure 22.- Continued.

| DEG. OF FREEDOM | QUAD ACCEL. (G/LB) OR (G/LB-IN) | NORM. QUADS (G(2)SEC(2)/LB-IN) | DEG. OF FREEDOM | QUAD ACCEL. (G/LB) OR (G/LB-IN) | NORM. QUADS (G(2)SEC(2)/LB-IN) |
|---|---|---|---|---|---|
| 1 | -0.4559E-05 | -0.2029E-02 | 41 | 0.2854E-04 | 0.1270E-01 |
| 2 | -0.1409E-04 | -0.6277E-02 | 42 | 0.1016E-03 | 0.4527E-01 |
| 3 | 0.2030E-04 | 0.9038E-02 | 43 | 0.2450E-04 | 0.1091E-01 |
| 4 | 0.5616E-07 | 0.2500E-04 | 44 | -0.6191E-05 | -0.2756E-02 |
| 5 | -0.3729E-06 | -0.1660E-03 | 45 | 0.5436E-04 | 0.2420E-01 |
| 6 | 0.1365E-06 | 0.6081E-04 | 46 | 0.1659E-04 | 0.7388E-02 |
| 7 | -0.2831E-05 | -0.1260E-02 | 47 | 0.4181E-04 | 0.1861E-01 |
| 8 | -0.9865E-05 | -0.4392E-02 | 48 | 0.9985E-04 | 0.4445E-01 |
| 9 | -0.3908E-04 | -0.1740E-01 | 49 | 0.4711E-04 | 0.2097E-01 |
| 10 | 0.2671E-06 | 0.1189E-03 | 50 | 0.4350E-04 | 0.1936E-01 |
| 11 | -0.2955E-06 | -0.1315E-03 | 51 | 0.1130E-03 | 0.5031E-01 |
| 12 | 0.8567E-07 | 0.3814E-04 | 52 | -0.1648E-05 | -0.7339E-03 |
| 13 | -0.1520E-04 | -0.6771E-02 | 53 | 0.4782E-04 | 0.2129E-01 |
| 14 | 0.6882E-05 | 0.3064E-02 | 54 | 0.4993E-04 | 0.2223E-01 |
| 15 | -0.1145E-04 | -0.5101E-02 | 55 | 0.7522E-05 | 0.3349E-02 |
| 16 | 0.2342E-06 | 0.1042E-03 | 56 | 0.7464E-06 | 0.3323E-03 |
| 17 | 0.1415E-06 | 0.6304E-04 | 57 | 0.7948E-04 | 0.3538E-01 |
| 18 | -0.9882E-07 | -0.4400E-04 | 58 | 0.4160E-06 | 0.1852E-03 |
| 19 | 0.5229E-04 | 0.2328E-01 | 59 | 0.7798E-07 | 0.3472E-04 |
| 20 | 0.3622E-04 | 0.1612E-01 | 60 | 0.1290E-06 | 0.5745E-04 |
| 21 | -0.3702E-04 | -0.1648E-01 | 61 | 0.1023E-04 | 0.4555E-02 |
| 22 | 0.1353E-04 | 0.6025E-02 | 62 | 0.1555E-04 | 0.6924E-02 |
| 23 | -0.5342E-04 | -0.2378E-01 | 63 | 0.1024E-03 | 0.4560E-01 |
| 24 | -0.8176E-04 | -0.3640E-01 | 64 | 0.3845E-06 | 0.1712E-03 |
| 25 | -0.1025E-03 | -0.4564E-01 | 65 | 0.1070E-05 | 0.4765E-03 |
| 26 | -0.4734E-04 | -0.2116E-01 | 66 | -0.1446E-06 | -0.6442E-04 |
| 27 | 0.8392E-04 | 0.3736E-01 | 67 | 0.7210E-05 | 0.3210E-02 |
| 28 | 0.1122E-03 | 0.4999E-01 | 68 | 0.1895E-05 | 0.8437E-03 |
| 29 | 0.1077E-03 | 0.4797E-01 | 69 | 0.4526E-04 | 0.2015E-01 |
| 30 | -0.7113E-04 | -0.3167E-01 | 70 | 0.2743E-06 | 0.1221E-03 |
| 31 | -0.1299E-03 | -0.5786E-01 | 71 | 0.1289E-05 | 0.5741E-03 |
| 32 | -0.7199E-04 | -0.3205E-01 | 72 | -0.1103E-06 | -0.4913E-04 |
| 33 | -0.9301E-04 | -0.4141E-01 | 73 | 0.4494E-05 | 0.2001E-02 |
| 34 | -0.1162E-04 | -0.5174E-02 | 74 | -0.2593E-04 | -0.1154E-01 |
| 35 | 0.1299E-04 | 0.5786E-02 | 75 | -0.1545E-03 | -0.6879E-01 |
| 36 | 0.8861E-04 | 0.3945E-01 | 76 | 0.3529E-06 | 0.1571E-03 |
| 37 | -0.3152E-05 | -0.1403E-02 | 77 | 0.1431E-05 | 0.6371E-03 |
| 38 | 0.2943E-04 | 0.1310E-01 | 78 | 0.3243E-07 | 0.1444E-04 |
| 39 | 0.7089E-04 | 0.3156E-01 | 79 | 0.6714E-04 | 0.2989E-01 |
| 40 | -0.3411E-04 | -0.1518E-01 | 80 | -0.1512E-04 | -0.6733E-02 |

(c) Generalized response data.

Figure 22.- Concluded.

## Plot Option

The plot option provides access to the plot routines. The following two options are available.

1. Stick plots on the digital plotter or graphic CRT generated by this routine are composed of node displacements or rotations as functions of elevation or station number about three mutually perpendicular axes. The shape of the perturbed structure is derived from the deflection data of the mass points. A typical stick plot is shown in figure 23. The columns of numbers at the bottom of each stick

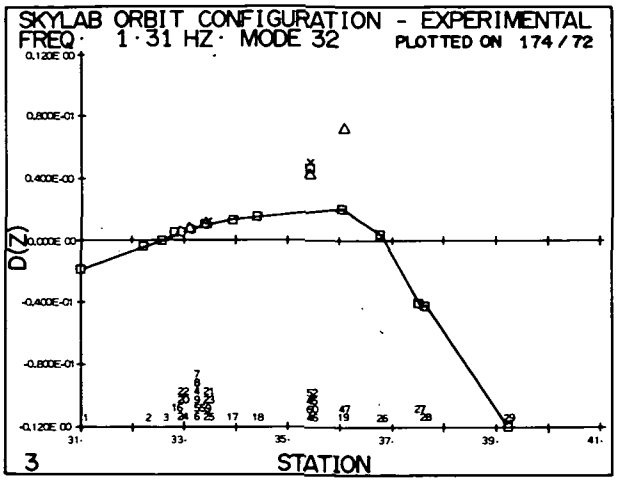


Figure 23.- Typical stick plot.

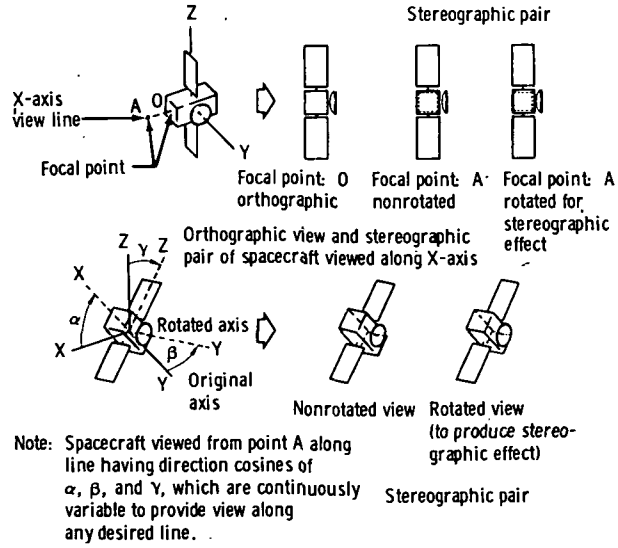


Figure 24.- Effect of varying plot parameters.

plot consist of the node numbers, arranged in the order of deflection. Only six plots (three translation and three rotation) are required to describe a structure, but the capability of plotting separate parts of the structure on different plots was developed to increase the clarity of presentation.

2. The routine for orthographic and stereographic plots on the digital plotter generates three orthographic and two stereographic views of the structure. Plotting parameters are manually entered on the keyboard to enable viewing of the structure at any angle and at any focal point. The utility provided by parameter selection is shown in figure 24. The stereographic plots, when viewed with a stereoscope, provide a three-dimensional view of the structure.

### Orthogonality Option

The orthogonality routine (ORTHO) provides for selecting the type of check, automatic or cross, to be made between analytical or experimental modes. In addition, the particular set of desired modes for orthogonality is entered through the CRT keyboard. Orthogonality is discussed in appendix C.

## TEST TECHNIQUES

The test techniques section comprises a discussion of several techniques used in testing with the AMTAS.

### Modal Tuning and Data Acquisition

The supervisor provides the algorithms for excitation control, real-time monitoring, and data acquisition for all modal operations. Upon selection of the supervisor through the controller, the initialization procedure is performed, followed by keyboard entry of the limit accelerometer parameters and respective response limits. The first operational entry is used to perform a wide-band sinusoidal sweep

with a selected exciter to obtain preliminary data of vehicle response to uniaxial, single-point force input. These data provide modal definition for use during tuning. Generally, most of these sweeps are performed before advancing to the other sequences. (In either the SUPSS or the ASUPS mode, two shakers can be driven simultaneously, although only one is actively servo controlled. The second shaker improves the quality of the excitation for better definition of bending or torsional modes when driving tangentially attached shakers.) In the SUPSS mode, three accelerometers can be selected for digital recording and concurrent co-quad plotting. Any number of accelerometers can be selected for analog tape recording in the ASUPS mode for subsequent off-line data reduction. This mode of operation is advantageous when many accelerometers are used for preliminary data analysis. The information resulting from wide-band sweeps consists of gross mode shapes or pairing with predicted analytical modes, approximate frequency of a mode, preferred shakers for a mode, and initial phase settings for shakers.

Modal tuning follows the initial wide-band sweeps and subsequent data analysis. The next four selection options, SUPTS, SUPTM, SUPSM, and SUPMD, are associated with the tuning operation. Modal tuning with multiple exciters, SUPTM, is the main process of modal excitation and mode identification and separation. Tuning with a single exciter, SUPTS, is a short form of tune multiple operation.

The modal tuning and acquisition sequence is initiated by selecting a target mode and determining the appropriate forcing distribution. A nominal force level is manually initialized on the master (primary) exciter. This exciter is selected by analysis of the analytical model data (plots and listings) and the experimental co-quad data derived from the single-exciter (ASUPS and SUPSS) sinusoidal sweeps.

The operator directs the operation by keyboard entry. After manual initialization of the forcing distribution, the low (LO) command returns the display update rate to the slow mode. The high (HI) update mode is automatically activated upon entry to a software module; therefore, forcing-distribution initialization is required. Returning to the slow update mode allows most of the computer time to be devoted to acquiring and reducing data. The data identifying the response accelerometers and reference load cell are entered into the CRT format before the operation begins. These transducers can be changed by the appropriate entry at any time during a given operation.

The modal response of the structure is optimized by varying the frequency of excitation and the forcing distribution (phase and level of the active exciters). While increasing quadrature values are noted on the co-quad displays, the frequency is incremented to maximize the quadrature value and to close the Lissajous pattern. The Lissajous pattern complements the co-quad displays and is useful in approaching an effective distribution. However, fine tuning is best achieved by observing small changes in the quadrature values because these effects cannot be detected in the Lissajous patterns. Lissajous patterns are normally formed by pairing exciter forces and respective driving-point accelerations. However, accelerations from other points of the structure may also be used, particularly when fine tuning the mode. As more exciters are activated, the resonance frequency will tend to shift downward. As this shift occurs, the frequency is incremented to below resonance, then increased in fine steps to peak the quadrature values. (See the following comments on hysteresis.)

In some instances, it may be advantageous to suppress participation of a neighboring mode rather than to attempt excitation of the target mode. A decrease in the coincident values indicates suppression of the undesired mode. The quadrature values must not decrease appreciably during the process.

After the forcing distribution is optimized, the frequency of resonance is established from a lower frequency to eliminate effects of hysteresis; hysteresis often distorts curves of response level as a function of frequency and may result in erroneous indications of resonance conditions.

Accelerometers at key points of the structure are surveyed to assess the adequacy of tuning. Co-quad values from several primary locations are tabulated for reference during subsequent operations.

The four options of the tuning process automatically sequence in a logical order: tune single proceeds to tune multiple, then to sweep multiple, and then to modal decay. However, any desired operation can be entered directly through the operation selection table, as shown in figure 13.

A sweep multiple operation can be performed at any time in the tuning process as an aid in defining the resonance condition, particularly if difficulties arise in the tune multiple operation. Performance of a narrow-band sweep can identify any neighboring problem mode and provide insight on suppression techniques. After completion of the final tune multiple sequence, a sweep multiple operation is normally performed for data purposes. The co-quad plots from these narrow-band sinusoidal sweeps are used in posttest analysis for an index of modal separation and for the calculation of damping values. Damping calculations are discussed in appendix D. One or more sweeps can be performed depending on the number of different accelerometers to be plotted.

When the co-quad data of the tune multiple and sweep multiple operations indicate that a mode has been properly separated and tuned, a modal decay is performed. Shaker excitation is removed, and the unfiltered signals from selected accelerometers are recorded on an oscillograph. The quality of the decay curves (fig. 25) provides another index of modal purity. If the structure decays smoothly with the absence of beating for the tuned mode, modal purity is good. If the modal purity is satisfactory, the sequence will be cycled automatically to the modal dwell operation for data acquisition. If modal purity is poor, the tuning iterations can be repeated. In tuning problem modes, it is sometimes helpful to acquire dwell data despite the impurities and to generate plots of the existing mode. These plots provide the visibility to define problem areas and to assess the adequacy of the existing exciter locations to properly excite the target mode.

The modal dwell operation begins with operator entry of bookkeeping data, mode identifier, and run number for documentation and data retrieval purposes. Excitation is reinstated, and the force servo maintains the predetermined forcing distribution. The automatic phase-lock feature can be activated if desired. After stabilization of the forcing distribution and response, data are acquired on the operator's CRT. Upon completion of data acquisition, the data are automatically reduced and stored on disk. (Note the position of the REDUC module in fig. 13.)

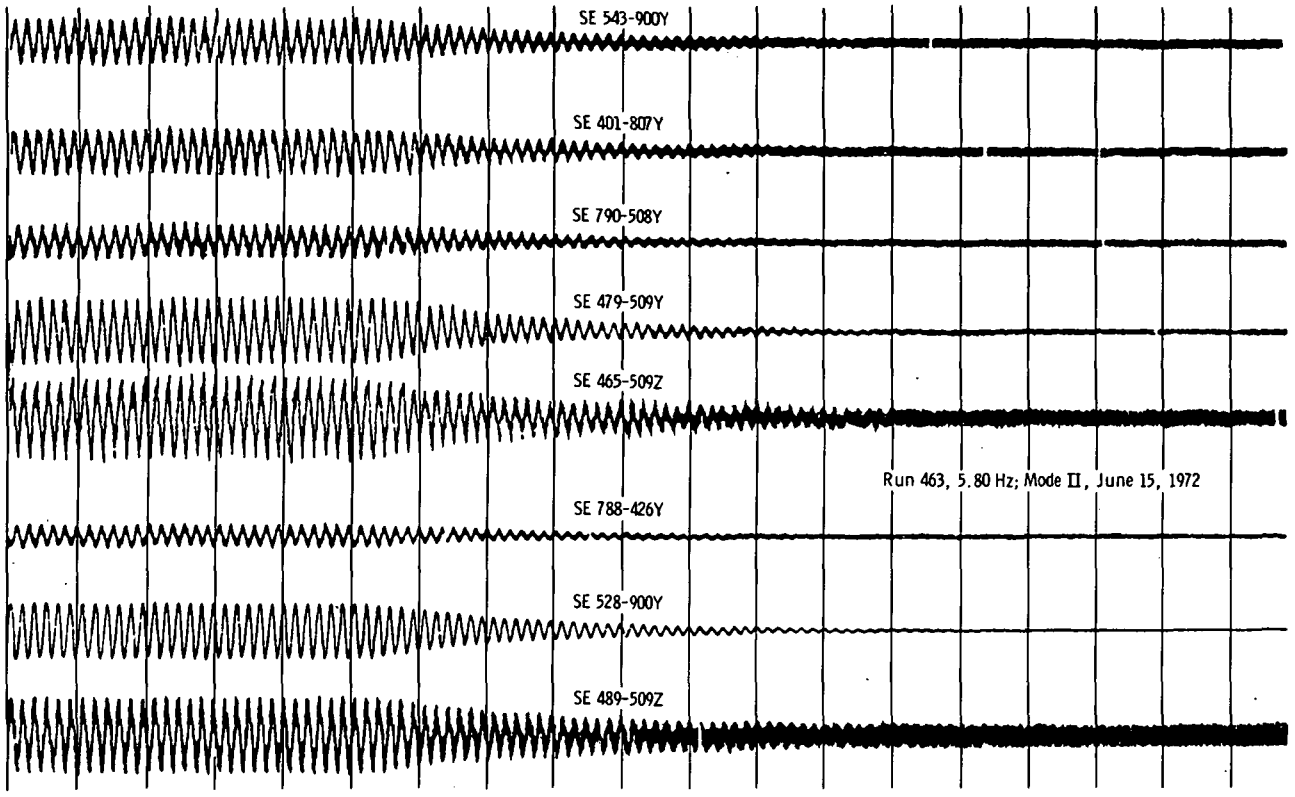


Figure 25.- Skylab orbital configuration modal decay curve.

## Co-Quad Plots

The data obtained from a typical sine sweep are in the form of three sets of force-normalized coincident and quadrature component values displayed on a digital X-Y plotter. The wide-band, force-normalized co-quad plots provide a means of identifying the resonant frequencies of the structure.

At a resonance frequency, the quadrature component of the data rises to a peak value and then declines while the coincident component decreases to a minimum, rises sharply crossing the zero axis when the quadrature is at a peak value, increases to a maximum, and gradually returns to the zero axis, assuming a positive quadrature peak. Polarities of the coincident value will reverse for a negative quadrature peak.

## Modal Plots

The stick plots are useful as a diagnostic tool, in addition to their normal function of providing a graphic description of a mode. Appropriate calibration values may be inserted on the data bus to simulate unit accelerations on all

transducers and unit forces on all load cells, and the SUPDW module may be used to acquire these calibration data. After reduction, the plotted data must appear as rigid-body translations on the stick plots. If not, there are errors in the translation equations. The trimetric (three planar views) set and stereographic pair provide a graphic capability for assessing the adequacy of a particular forcing distribution in exciting a given mode.

An automatic scaling feature provides maximum resolution. (The operator may override this feature and specify a particular scale, if desired.) For comparison purposes, however, scaling for the total set of translation plots is calculated on the basis of all data to be plotted. Similarly, the scale for rotation is calculated for all plots.

A set of stick plots may be made on the alphanumeric-graphic CRT (quick look) or the digital plotter (report-quality hard copy). These instruments plot degree of freedom as a function of station number; the plots are formatted to provide perturbation definition along each axis.

### Decay Curves

Decay curves are used to assess the purity of a mode by noting the amount of beating present. Curves generated during a modal decay with only the target mode excited will reflect no beating.

### Off-Line Co-Quad Analysis

The off-line co-quad processing (by a central reduction laboratory) is accomplished by digitizing and reducing the taped analog data to the desired engineering unit output. These reduced data permit assessment of the force-servo subsystem operation and detection of the approximate frequencies at which the response of the structure is significant.

## RECOMMENDATIONS FOR FUTURE APPLICATIONS

During the application of AMTAS to the Skylab modal survey, several improvements to the system were defined. Improvements that represent significant increases to overall capability are discussed in the following paragraphs.

### Test Article Suspension System

The ancillary suspension system should become an integral part of the AMTAS to permit computer control of the suspension system. Single-parameter (position) or dual-parameter (load or pressure and position) feedback can be used for positive control of the test article suspension.

### Technical Writer's Log Input

An additional CRT/keyboard display unit should be incorporated for use by the technical writer. Test comments could be composed in the local mode using the edit features of the unit. After the text is completed, the comments could be entered by a send command. The entire sequence log, including comments, should be displayed on the line printer and stored on digital magnetic tape.

### Modal Survey Simulator

Training could be facilitated if a simulator software package were developed and included as an on-line option. Data stored during the Skylab modal survey could be used for a realistic simulation of a modal survey, including wide-band and narrow-band sweeps, tuning operations, modal decays, and dwells. This approach would eliminate the need for a structure for training purposes.

### Test Procedure Display

A separate CRT (monitor only) unit should be incorporated to display the test procedure with slaved monitor units at each test station. This arrangement would eliminate the complexity of following the test operation, because the main-line program will automatically display the correct page of the procedure and scroll it forward as the test progresses.

## CONCLUDING REMARKS

The design goals of the automatic modal tuning and analysis system — providing positive control of test conditions, rapid data acquisition and reduction, immediate documentation of modal response characteristics, and a high degree of specimen safety — were achieved. This unique system provided data in a meaningful form to the data evaluation team, which rapidly evaluated the data and selected specific modes from the numerous candidate modes observed. The selected modes were individually excited, and pertinent data were acquired. The automatic modal tuning and analysis system described herein is capable of meeting the requirements for a modal survey of any structure comparable in size and complexity to the Skylab payload. The techniques and methods employed in the system will enable expansion to meet the requirements of larger structures.

Lyndon B. Johnson Space Center
National Aeronautics and Space Administration
Houston, Texas, January 16, 1975
961-21-31-05-72

# APPENDIX A

## SKYLAB TEST ARTICLE

The automatic modal tuning and analysis system provides the capability for performing a modal test survey of a large and complex test article having resonance frequencies from 0.1 to 100 hertz. The Skylab orbital assembly, shown in figure A-1, is an example of such a test article to which the system has been applied.

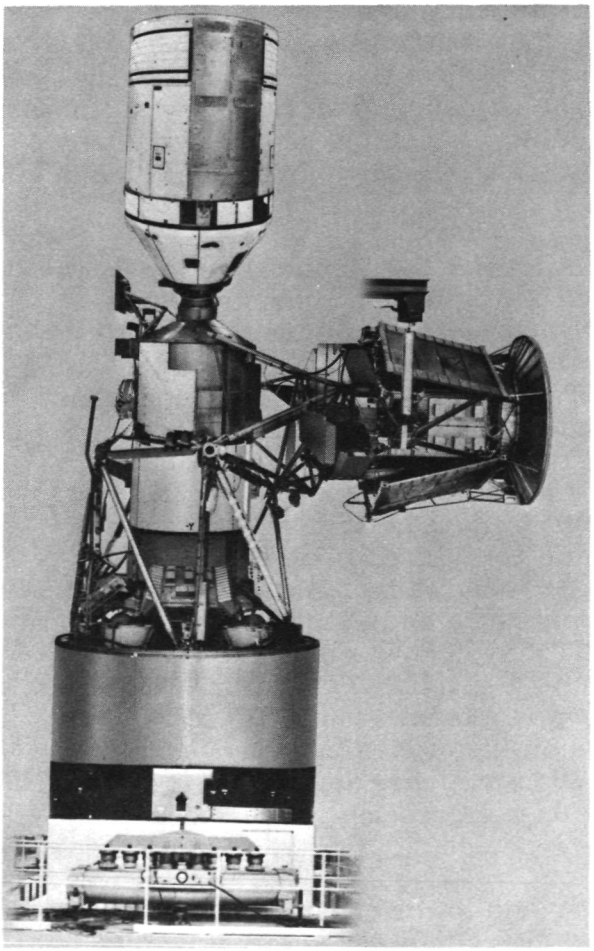

Figure A-1.- Skylab payload in orbital configuration.

The Skylab assembly orbital test configuration consisted of the Vibration and Acoustic Test Facility (VATF) base ring, the orbital workshop (OWS) forward skirt, the instrumentation unit (IU), the fixed airlock shroud (FAS), the airlock module (AM), the deployed Apollo telescope mount (ATM), and the inverted command and service module (CSM). The ATM includes engaged launch and orbital locks and four undeployed solar arrays. The entire cluster was suspended axially by air springs. With the exception of the CSM, the launch test configuration had all the same subassemblies plus the payload shroud. The test article in each configuration weighed approximately 54 400 kilograms (120 000 pounds) and was approximately 21 meters (70 feet) high.

The vehicle suspension systems used for the Skylab launch and orbital test configurations were designed to provide free-free support and made use of soft pneumatic spring units. Although to rigidly support the vehicle in the test facility would have permitted analysis of the test vehicle as a cantilevered beam, the soft suspension was preferred. Some of the reasons for this preference are as follows.

1. Before modal testing, the launch configuration was subjected to a high-force dynamics test of 444 800 newtons (100 000 pounds) force peak. For this test, isolation of the vehicle and the

excitation system from the facility was required for facility protection. Therefore, a soft pneumatic spring system was necessary.

2. If a rigid support had been used, boundary conditions would have been extremely difficult to define, but definition would have been necessary to determine the effects and contributions of the support to modal responses of the test article.

3. Regardless of the type of support used for the remainder of the vehicle stack, a vertically soft spring was required for the deployed ATM in the orbital configuration. A vertical spring allowed for correct relative displacements during modal excitation. Failure of the ATM air spring with the remainder of the stack rigidly supported could have damaged the ATM and attaching hardware.

The two Skylab vehicle configurations in the vertical position provided a simulated free-free or unrestrained environment in which to excite and measure the natural elastic vibration modes of the structure. Low stiffness was obtained in the vertical direction through the use of pneumatic springs consisting of multiple lift elements mounted on a plenum tank having a large adjustable volume. Low stiffness in the lateral directions was obtained by suspending the vehicle on relatively long rods to produce pendulum motions that were essentially linear for the amplitude of the motions experienced during the modal test.

The two suspension systems are shown in figures A-2 (launch) and A-3 (orbital). The suspension system for the launch configuration consisted of three identical air-spring units mechanically connected through pendulums to a ring fixture to which the lower surface of the Saturn S-IVB forward skirt was attached. These three air-spring units functioned and were operated as a single suspension system. For the orbital configuration, the spacecraft modules were divided into three subassemblies: (1) the inverted CSM; (2) the deployed ATM; and (3) a subassembly consisting of an OWS forward dome and skirt, the FAS, the AM, the multiple docking adapter (MDA), and the deployment truss. Five air-spring units were used, as shown in figure A-3. In the orbital configuration, the airlock subassembly was suspended on the same ring fixture, pendulums, and plenums used for the launch configuration, but the operating pressure and natural frequency were adjusted to match the other two systems. The ATM system was made up of one air-spring unit attached with a single pendulum to a special ATM fitting. The CSM system consisted of a single air-spring unit but was attached to two fittings on the aft bulkhead of the service module using two pendulum rods. The suspension systems including control systems were designed to minimize static-load transfers across the CSM/MDA interface and the ATM/deployment assembly interface to eliminate degrading effects on modal response data.

Safety features of the system include upper and lower mechanical stops for each air-spring unit or vehicular subsystem and lateral clearances from facility structures. The most important safety feature is inherent in the soft-spring suspension. If an air spring failed, the maximum load across the vehicle interface would not exceed the load required to displace the remaining air springs to their lower stops. These stops were set at 3.8 centimeters (1.5 inches) below the nominal operating height of each subassembly, and the maximum interface loads would have been well below the allowable spacecraft design limits. A separate safety feature

of the controls is an overtravel monitor that is used to terminate excitation automatically when the vehicle approaches one of the mechanical stops.

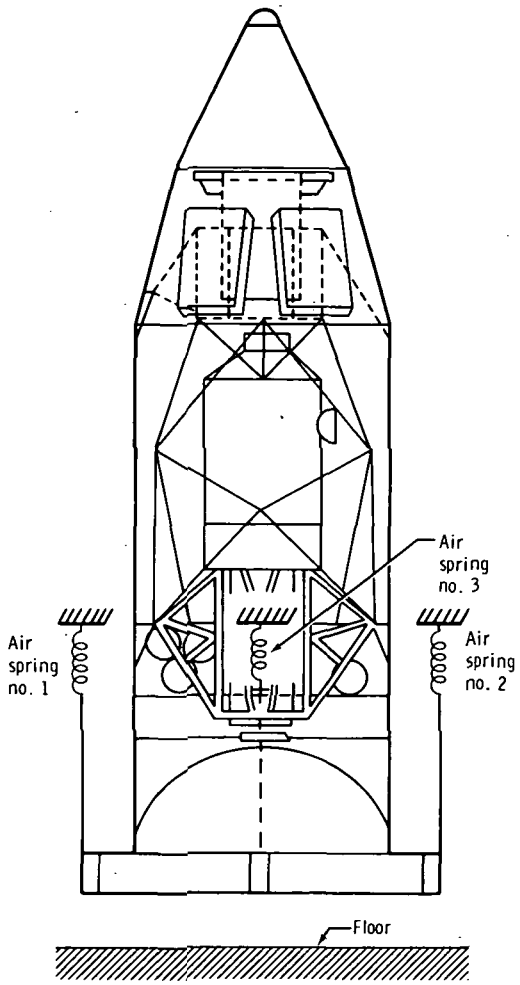


Figure A-2.- Suspension of payload assembly launch configuration modal survey.

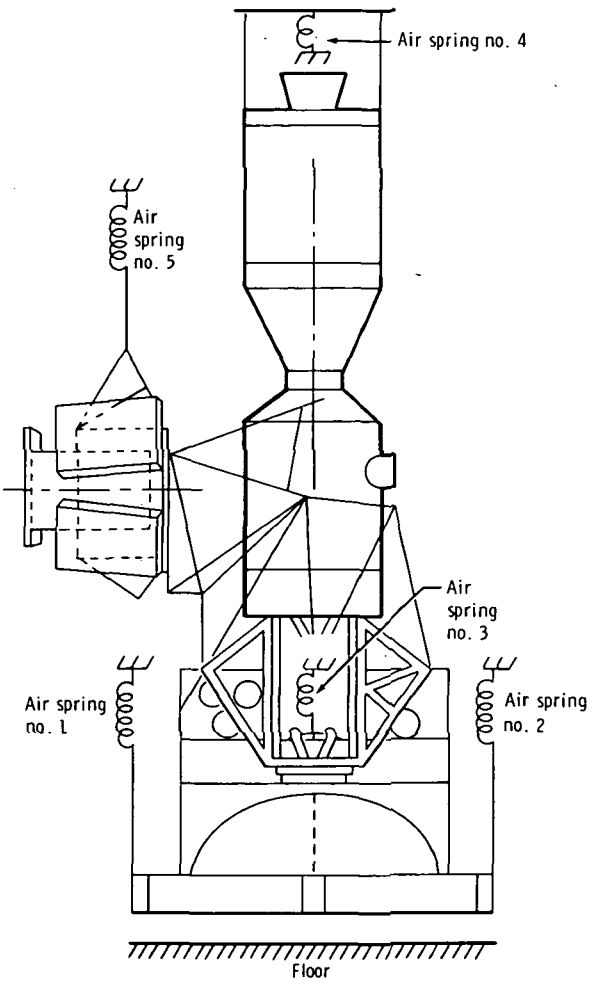


Figure A-3.- Suspension of payload assembly orbital configuration modal survey.

The exciter supports were soft mounted for one test and hard mounted for the other because of the differing frequency ranges of the Skylab launch (5 to 50 hertz) and orbital (0.8 to 20 hertz) test configurations. For the launch configuration, all horizontal exciters were pendulum mounted with soft (35 N/cm (20 lb/in.)) mechanical springs in series with the support rod. The same springs were used for supporting the vertically oriented exciters. The exciters weighed approximately 150 kilograms (330 pounds); this weight resulted in a vertical natural frequency of 0.75 hertz.

For the orbital configuration, most of the exciters were hard mounted. However, in a few locations, pendulum mounting was used because of poor exciter position relative to adequate support structure. The pendulum-mounted exciters required additional reaction mass loading to maintain adequate stroke capability at the lower frequency limit. Additional mass of approximately 900 kilograms (2000 pounds) was attached to these exciters. The arrangement of exciters for the orbital configuration modal survey is depicted in figure A-4.

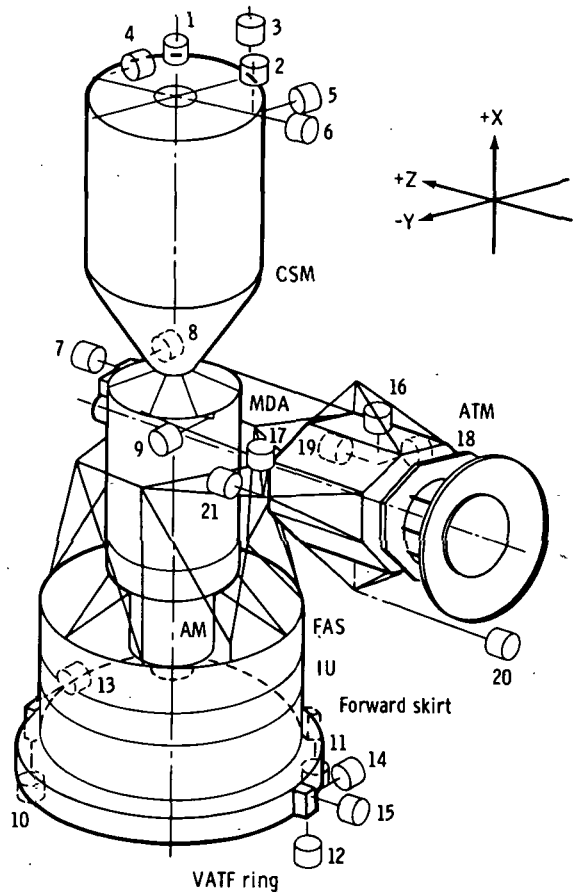


Figure A-4.- Exciter arrangement for orbital configuration modal survey.

# APPENDIX B

## CO-QUAD ANALYSIS OF MODAL RESPONSE DATA

Co-quad analysis represents a recent and important advance in modal survey technology. The term co-quad is used to refer to the in-phase (coincident) and out-of-phase (quadrature) components of one signal that are in phase and out of phase, respectively, with another signal. In applying the co-quad technique to reducing modal survey data, the acceleration response signal is resolved into coincident and quadrature components with respect to the signal representing the force applied to the structure under test. (See fig. B-1.)

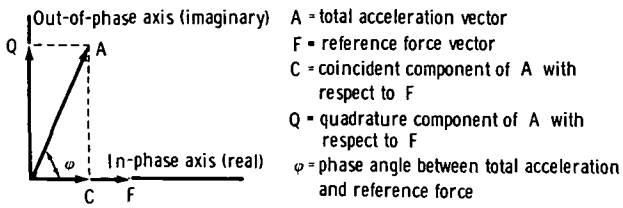


Figure B-1.- Co-quad component definition.

It is appropriate to examine the phase relationships that exist during steady-state vibration to acquire the background necessary to fully appreciate the power of co-quad analysis. W. T. Thomson (ref. 1) succinctly interprets these phase relationships for cases of steady-state excitation at frequencies below resonance, at resonance, and above resonance.

Force and acceleration signals are used for co-quad analysis because they are readily available from force transducers and response accelerometers. Signals from velocity or displacement transducers, or from another accelerometer, could be used as a reference for resolving response accelerations into their coincident and quadrature components. However, the proper phase relationships between the reference signal and the response acceleration must be known to interpret the results properly. The phase relationships for force F, acceleration A, velocity V, and displacement D for conditions below resonance, at resonance, and above resonance are given in table B-I. As shown in table B-I, with force as the reference signal and acceleration as the response signal, acceleration is 90° out of phase with force at resonance. Below resonance, the phase angle $\phi$ is between 90° and 180°; above resonance, the phase angle is between 0° and 90°. As a function of frequency, the co-quad response of acceleration with respect to force is shown in figure B-2. At resonance, the quadrature value is at a maximum and the coincident value is at a minimum. Data resulting from a slow sweep through a resonant frequency point, at a linear rate, are useful in assessing the modal qualities in the following ways. First, such data indicate the frequency of resonance (maximum quadrature point); second, such data give a clear picture of any modal content at adjacent frequencies (minor quadrature peaks or other perturbations to a smooth rise and fall of the quadrature curve); and, third, data that may be used to calculate the percent of critical damping are contained in the coincident spectrum.

TABLE B-I.- PHASE RELATIONSHIPS FOR BASIC STRUCTURAL CONDITIONS

| Phase relationship | Basic structural conditions[a] | | |
|---|---|---|---|
| | Below resonance (spring control) | At resonance | Above resonance (mass control) |
| F lags A by | $90° < \phi \leq 180°$ | 90° | $0° \leq \phi < 90°$ |
| F lags V by | $0° < \phi_1 \leq 90°$ | 0° | $-90° \leq \phi_1 < 0°$ |
| F lags D by | $-90° < \phi_2 \leq 0°$ | -90° | $-180° \leq \phi_2 < -90°$ |

[a]Where $\phi_1 = \phi - 90°$; $\phi_2 = \phi_1 - 90°$.

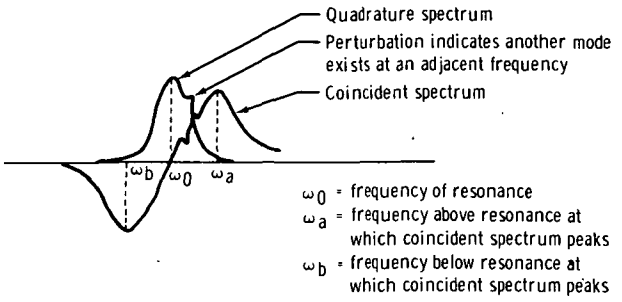


Figure B-2.- Narrow-band co-quad spectrum.

Digital filtering of the data with a tuned center frequency and a variable bandwidth enables performance of co-quad analysis not only during data acquisition at a resonance frequency but also during a sweep operation in which the band-pass filter must track the frequency of excitation. The variable-bandwidth filter is most useful during acquisition of response data from a structure having a high modal density, during which the adjacent modes cannot be completely suppressed with the available exciters.

Aliasing, or foldover, of data into the frequency range in which data must be accurate (within the filter bandwidth) is prevented by using low-pass filters to eliminate input signal components above a given frequency. This result is achieved by maintaining the 3-decibel cutoff frequency at a value less than half the sampling rate. The case in which the cutoff frequency $F_c$ of the low-pass antialiasing filter is set to greater than half the sampling rate SR is illustrated in figure B-3. Any value is permissible for $F_c$ as long as the resulting image frequencies do not fall below the value obtained by adding one-half the filter bandwidth BW to the frequency of excitation $F_e$.

The total acceleration vector is resolved into its coincident and quadrature components in two steps. First, the complex Fourier transform coefficients are computed for both the reference and response signal. The terms used are as follows: $A_f$ is the real coefficient for force, $B_f$ is the imaginary coefficient for force, $A_a$ is the real coefficient for acceleration, and $B_a$ is the imaginary coefficient for acceleration. The coincident and quadrature components are obtained by the following cross-multiplication process.

$$\left.\begin{aligned} Co &= A_f \cdot A_a + B_f \cdot B_a \\ Quad &= A_a \cdot B_f - A_f \cdot B_a \end{aligned}\right\} \qquad \text{(B1)}$$

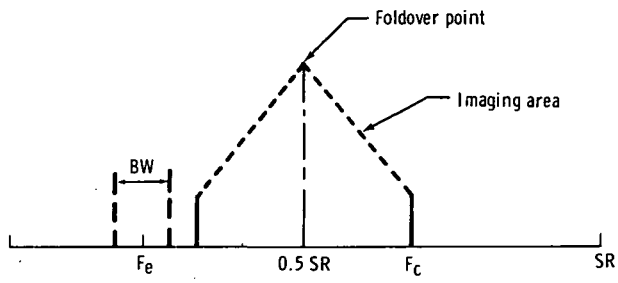


Figure B-3.- Antialiasing of input data.

# APPENDIX C

## ORTHOGONALITY

The modal deflections of a measured mode are the elements of a column matrix. This modal column of the n degree-of-freedom system in the rth mode is represented by $[\Theta_r]$ where each element $\Theta_{i,r}$ equals deflection at point i (where i = 1, n). This modal column is also called the rth eigenvector and can be thought of as a vector in n-dimensional space where each element of the column is a component of the vector in the corresponding coordinate direction. For an n degree-of-freedom system, there are n such eigenvectors. Each eigenvector and associated eigenvalue (resonance frequency) will satisfy the equation of motion for the system in free vibration.

The generalized mass $G_r$ of the system for the rth measured mode is given by

$$G_r = \left[\Theta_r\right]^T [M] \left[\Theta_r\right] \tag{C1}$$

where T denotes the transpose of the mass matrix [M]. The set of eigenvectors obtained experimentally should be orthogonal with respect to the mass (or stiffness) weighting matrix. This orthogonality relationship, with mass as the weighting matrix between the rth and sth modes, is expressed as

$$\left[\Theta_r\right]^T [M] \left[\Theta_s\right] = 0 \tag{C2}$$

Mass coupling between the rth and sth modes results in a value other than zero. Therefore, the mass coupling C between the rth and sth measured modes is defined as

$$C_{r,s} = \left[\Theta_r\right]^T [M] \left[\Theta_s\right] \tag{C3}$$

The magnitude of mass coupling $\delta_{r,s}$ between the rth and sth measured modes can be assessed by comparison with the rth and sth generalized masses.

$$\delta_{r,s} = \frac{C_{r,s}}{\left(G_r \cdot G_s\right)^{\frac{1}{2}}} \tag{C4}$$

The generalized mass matrix $[G]$ is defined as $[G] = [\theta]^T[M][\theta]$ where the lack of a subscript for the modal matrices signifies that the complete set of eigenvectors is included. The generalized mass matrix will contain diagonal elements representing the generalized mass for each mode and off-diagonal elements representing the mass coupling terms. The generalized mass matrix can be characterized by

$$\left[G_{r,s}\right] = \begin{bmatrix} G_r & C_{r,s} \\ C_{r,s} & G_s \end{bmatrix} \tag{C5}$$

where $G_r$ and $G_s$ are the generalized masses of modes $r$ and $s$, respectively, and $C_{r,s}$ is the coupling between modes $r$ and $s$. The nondimensional magnitude of mass coupling $\delta_{r,s}$ can be computed by using the elements of the mass matrix. It is desirable to normalize the elements of each modal column to unity generalized mass for the particular measured mode. Normalization is possible because amplitude is not a property of normal modes. Denoting the normalized modal column of the rth measured mode as $[\phi_r]$, each element is obtained by dividing by the root of the rth generalized mass.

$$\phi_{i,r} = \frac{\theta_{i,r}}{\left(G_r\right)^{\frac{1}{2}}} \tag{C6}$$

The generalized masses of each normalized mode will be unity.

The difficulty in attempting to obtain absolutely orthogonal modes (with zero-mass coupling) can be realized by noting the causes of error. The distributed mass of the structure is represented by discrete mass elements to form a mass model. The transformation equations include terms to determine the displacements of the center of gravity and rotations about the principal axes of inertia of each mass element from components of acceleration measured at various physical locations. The accuracy of the determined mass coupling, or orthogonality, depends on the accuracy of the theoretical mass model, the transformation equations, and the experimental data. Two modes can be orthogonal, but it is possible that these modes are not normal to the remaining modes of a set even though they appear to meet orthogonality conditions when considered as a pair without regard to the other normal modes. Orthogonality is a necessary but not sufficient condition that the mode under consideration is a normal mode of the structure.

In a frequency range having a high modal density, the auto-orthogonality check is a convenient method of comparing analytically predicted and experimentally derived modes. This comparison is made by using orthogonality checks between the mode being investigated and all analytical modes predicted to be within the general frequency area of the mode of interest.

## APPENDIX D

## DAMPING CALCULATIONS

The most convenient method for calculating the damping factor is to determine the frequency points of maximum and mimimum coincident response. In figure B-2, the minimum frequency $\omega_b$ occurs below resonance and the maximum frequency $\omega_a$ occurs above resonance. The damping factor $\xi$ is a function of the ratio of these frequencies.

$$\xi = \frac{\left[\left(\frac{\omega_a}{\omega_b}\right)^2 - 1\right]}{2\left[\left(\frac{\omega_a}{\omega_b}\right)^2 + 1\right]} \tag{D1}$$

An alternate method is to use the relationship based on the logarithmic decrement of the decay curve given as

$$\xi = \frac{1}{2\pi n} \log \frac{Y_0}{Y} \tag{D2}$$

in which the damping factor is a function of the initial amplitude $Y_0$ and the final amplitude $Y$ of the peaks of a decay curve, as shown in figure D-1, and $n$ is the number of cycles included within the initial and final amplitude peaks.

Figure D-1.- Modal decay curve.

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