THE APPLICATION OF DIGITAL COMPUTERS TO NEAR-REAL-TIME PROCESSING OF FLUTTER TEST DATA

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SUMMARY

A description of procedures used in monitoring, analyzing, and displaying flight and ground flutter test data is presented. These procedures include three digital computer programs developed to process structural response data in near real time. Qualitative and quantitative modal stability data are derived from time history response data resulting from rapid sinusoidal frequency sweep forcing functions, tuned-mode quick stops, and pilot-induced control pulses. The techniques have been applied to both fixed- and rotary-wing aircraft, during flight, whirl tower rotor systems tests, and wind tunnel flutter model tests.

An hydraulically driven oscillatory aerodynamic vane excitation system is described. This system was recently utilized during the flight flutter test programs accomplished during Lockheed L-1011 and S-3A development.

INTRODUCTION

The present day costs of prototype/development flight vehicles and overall demands on flight testing time require the flutter engineer to minimize both flight and calendar time associated with flutter substantiation and flight envelope clearance. This objective must be accomplished while maximum safety of flight to the flight crew and vehicle is maintained. Test and data analysis procedures must also be developed to minimize the risk of structural damage and/or loss of the high cost, dynamically scaled wind tunnel flutter models normally used during the pre-prototype phase of a flight vehicle development program. These objectives can be attained only by a well-coordinated test program which utilizes reliable procedures of instrumentation, signal conditioning, excitation technique, and data transmittal/storage/retrieval/display, properly integrated and compatible with the particular characteristics of the test vehicle.

The installation of special sinusoidal excitation devices, although desirable, can be justified only for those cases where the stability of a number of flutter-significant modes must be monitored, or for those cases where alternate or more economical excitation techniques, such as control pulses, do not adequately excite the modes of interest. In investigating the effect of relatively minor design changes which arise during the operational phase of an aircraft, such as control system changes, external store additions, and significant mass or stiffness variations, alternate excitation methods which do not demand special purpose hardware installations may be used. These methods include the well-known control pulse (manual or electrical) for low frequency modes generally less than 10 Hz, as well as recent developments in computerized data analysis techniques applied to turbulence-induced structural response data. The latter methods rely primarily on various Fourier transforms and spectral analysis procedures to determine modal frequency and damping characteristics. Examples of such techniques are described in references 1, 2, and 3.

This paper briefly describes the various flutter testing techniques utilized at the Lockheed-California Company in recent years as applied to several major flight vehicle programs. Primary emphasis is placed upon the online data monitoring capabilities made possible by the availability of modern computerized data handling systems.

Proper acknowledgement should be given to several associates at the Lockheed-California Company who were instrumental in developing, and making operationally practical, the techniques described in this paper.

Edmund A. Bartsch and Darrow Richardson developed the real-time decay program and the real-time response program. Bill Kobayashi developed the peak plot analysis with contributions made by Joe Buttitto, Burt McCorkle, Bridget Shycoff, and Erick Sturcke.

MODAL EXCITATION

So that the flutter-significant modes of the Lockheed L-1011 aircraft could be properly evaluated, an hydraulically driven oscillatory aerodynamic vane excitation system was developed and installed on the wingtips and stabilizer tips. The same system was later used during the S-3A flutter tests, being mounted on the aft fuselage. The vane actuators were developed by Royal Industries, Santa Ana, California. The aerodynamic vanes were designed and fabricated at Lockheed by using helicopter rotor blade design and fabrication techniques, which provided the required structural capability to withstand the extreme inertial and aerodynamic loadings imposed on the vanes at the required frequencies. Photographs of the vane installation and control units are shown in figures 1 and 2.

Salient features of the excitation system are:

A. It provides constant and selectable sinusoidal force over the frequency range of from 0.5 to 25 Hz for L-1011 application and 2.5 to 50 Hz for S-3A application.

B. It utilizes an automatic linear period frequency sweep function. Sweep time/rate is selectable. The sweep rate utilized during the L-1011 program optimized modal response, minimized sweep time, and optimized frequency shift due to sweep rate. The S-3A sweep rate optimized response amplitude/test time.

C. The installed unit weight is approximately 46 kilograms.

D. The airfoil used was symmetrical with 53-cm span and 46-cm chord. The vane was mass balanced with center of gravity at the axis of rotation (20% chord). The aerodynamic center, as determined by wind tunnel tests, was approximately 1.25 cm aft of the axis of rotation, minimizing actuator force requirements. Blunt trailing edges were added to the vanes to ensure a zero lift trail stability when unpowered.

E. The vane force capability was ±1000 newtons at 200 KEAS with proportionally higher forces available at higher speeds. The maximum vane oscillatory angle of attack was $\pm 15^{\circ}$. The force on each vane was individually selectable.

F. Automatic fail-safe features were designed into the actuator control system to limit vane force, vane amplitude, and/or aircraft structural response.

G. There were provisions for manually tuning particular modes of interest and stop vanes at zero lift position within less than 1 cycle.

H. The vanes can be driven either in phase or 180° out of phase as required to excite symmetric or antisymmetric airplane modes.

In addition to the use of the oscillatory vanes to provide modal excitation, certain modes were investigated by using control pulses or electrically commanded symmetric aileron impulses. In the case of certain wind tunnel flutter model tests, modal damping characteristics have been determined by applying the peak plot data analysis method to model response time histories excited by existing wind tunnel turbulence.

The choice of excitation is based on the specific modes of interest, cost considerations, and data analysis procedure to be used.

DATA ANALYSIS METHODS

Real-Time Decay Analysis

The real-time decay analysis program was developed to analyze telemetered flight flutter test data by use of an online computer and to help make a rapid determination of the damping of structural modes excited either by control pulses or by tuning with sinusoidal forcing devices and quick-stopping the excitation input.

The decay analysis program is based on the well-known assumption that the decay time history of the free oscillation following a pulse or quick stop is an exponential function. A plot of the log magnitude of the decay versus time is, therefore, a straight line. The output of the real-time decay program is a plot of the log of the successive half-cycle amplitudes versus number of half cycles, which is proportional to time if constant frequency of decay is assumed. The compute mode of the program is triggered by a pilot- or ground-initiated flag signal just prior to the control pulse input or by a flag signal automatically generated just prior to the oscillatory vane stop electrical command. When the compute mode is triggered, the computer processes the time history data as follows:

It searches for extreme values, maxima and minima, in such a way that each successive extreme value Y_i is determined and stored (fig. 3).

It calculates the double amplitude D_i for each half cycle, by the equation:

$$D_i = \left| \frac{1}{2} (Y_{i-1} + Y_{i+1}) - Y_i \right|$$

where i = 1,2,.... N-1, with $N \leqq 40$, a practical maximum number of half cycles.

The logarithm of the double amplitude D_i is calculated and normalized to 1.0 for the maximum value as follows:

$$LD_i = \log_{10} D_i - \log_{10} D_{i_{max}} + 1.0$$

A high-speed line printer is utilized to rapidly plot the normalized logarithm LD_i versus i, the number of half cycles. A typical example of the printed output is shown in figure 4. In previous applications, up to nine response parameters have been simultaneously analyzed and plotted within 30 to 40 seconds after the control pulse or quick stop.

Using engineering judgment, the engineer can fair a straight line through the plotted data and rapidly determine a quantitative damping value using a transparent overlay.

As noted in figure 4, the printout format serves as a convenient data-keeping device by identifying the following:

(1) test number
(2) flight number
(3) date
(4) run code number
(5) response parameter number/identification
(6) equivalent airspeed, Mach number, and pressure altitude at the time of pulse calculated from telemetered pressure measurements
(7) type of signal conditioning (filtering) utilized

(8) a printout of least-squares linear curve fit of the function LD_i versus i between the first maximum LD_i, identified as S, and a number of consecutive half cycles (M). The calculated value of structural damping (g), percent error (E%), and the average frequency (FM) over the computer-selected decay region are also printed

If the computer-selected decay region agrees with the flutter engineer's judgment, the damping and frequency can be taken directly from the printout. In addition, these computer-calculated values of g and FM can be digitally displayed in the data-monitoring area during flight.

Before the response time history signals are used as input to the real-time decay analysis program, the telemetered data are filtered through analog filters selected to isolate the anticipated modes of interest, depending on proximity and response amplitude of adjacent modes. The units used are selectable as low pass, high pass, or band pass filters, and they reliably condition exponentially decaying signals having structural damping rates of up to 25%. The analog signals, after proper filtering, are digitized in computer-compatible format at a rate of 500 samples per second prior to processing. A typical flow chart of a PCM data acquisition and monitoring configuration is shown in figure 5.

This analysis method is applicable for modal response cases where the mode is excited to an initial level of approximately three times the average level of response to random and atmospheric turbulence forcing levels. In addition, the technique relies heavily on engineering judgment in selecting the proper time slices. The computer program does, however, minimize the time and manual plotting effort previously required in analyzing free decay response data.

Real-Time Response Analysis

The real-time response program was developed primarily to provide rapid evaluation of the stability trends relative to a large number of modes as a function of airspeed. This technique is utilized when sinusoidal frequency sweep forcing devices are available on the test aircraft. Again, computer-processed data are available within approximately 30 seconds after the end of the sweep excitation. Typical sweep times are 40 to 60 seconds for a frequency range of 3.0 to 50 Hz. The sweep function used, though not a requirement, was a linear period sweep defined by the relationship

$$F(t) = \frac{F_o}{1 + a F_o t}$$

where

$F(t)$ = frequency at time t - Hz

F_o = frequency at time t = 0 - Hz

t = time = sec

a = dimensionless sweep rate

This function was selected as the best compromise between response amplitude, frequency shift, and time required to sweep through the desired frequency range. The response characteristics resulting from a linear period sweep were based on a study conducted by Edmund A. Bartsch and contained in Lockheed Report LR 16484, "Flight Flutter Testing Method."

Typically, nine response parameters are processed simultaneously. The response analysis is based on the assumption that the response ratio varies inversely as the modal damping rate. Plots are maintained to track relative response versus equivalent airspeed (see figure 6 as a typical example).

The response time history signals of each parameter are preconditioned, prior to being used as input to the computer program, through constant bandwidth (±2.5 Hz) tracking filters to minimize extraneous responses and high frequency noise. The tracking filter center frequency is controlled by the telemetered function generator signal which drives the oscillatory aerodynamic exciter vanes. The analog outputs of the tracking filters are then digitized at a rate of 500 samples per second and converted to engineering units for processing. Flag signals are used to trigger sweep-start and sweep-stop time in the computer. The sweep-stop signal causes the computer to stop receiving data, complete calculations, and start printing results. A typical real-time response analysis printout is shown in figure 7.

The computer program processes the time history data as follows:

It determines input and response amplitudes. The input function is the output of a strain gage bridge on the oscillating vane which is calibrated to measure vane normal force.

Input frequency at time of maximum response is calculated from the average period of the three previous and the three subsequent cycles of the input function.

It determines the time at which maximum and minimum response amplitudes occur, eliminating minor or transient fluctuations by a minima criteria identified as a "window," retaining and printing out only the significant response maxima and minima.

The results of the real-time program are presented in tabular form (figure 7). A separate sheet is printed for each response parameter of interest. As noted in figure 7, the following data are printed out versus elapsed time from sweep-start for all response maxima and minima which satisfy the "window" criteria specified within the swept frequency range.

Time of input peak in seconds (time of max. and min. response)

Input period in seconds

Input frequency in Hz

Vane input amplitude in pounds

Response amplitude in engineering units (i.e., lb, in-lb, acceleration (g))

Response ratio in engineering units

In addition to the response ratio, and general test identification, the following information is also printed:

Start and stop time of sweep

Indicated airspeed

Equivalent airspeed

Altitude

Mach number

The identification of modal maxima is made by the flutter engineer, based on frequency and relationship to response data at previous airspeeds. Both symmetric and antisymmetric sweeps are normally made to evaluate all pertinent modes.

Peak Plot Data Analysis Program

The peak plot data analysis program was developed at the Lockheed-California Company and is described in detail in Lockheed Report 25111, "Fourier Transform Analysis," dated March 31, 1972. This technique has been used at Lockheed to obtain modal frequency and damping data from time history data obtained from rotor system whirl tower tests, wind tunnel flutter model tests, and L-1011 and S-3A flight flutter tests. This method is utilized for those particular modes where the modal data of interest have a high level of signal contamination or extraneous response of adjacent modes. The peak plot program is available to the flutter engineer as an interactive computer graphics program which allows nearly instantaneous iterative solutions to be obtained. Simple light pen commands can be used to optimize data plotting and solution displays. Hard copies of desired data plots are easily obtained.

The peak plot method may be briefly described as follows:

The Cooley-Tukey fast Fourier transform (FFT) algorithm is applied to the digitized time history test data sample in order to generate a plot of the log of the Fourier transform, log $F(\omega)$, as a function of the log of the frequency, log (ω). The frequency of the mode or modes of interest is "coarsely" displayed by the light pen detecting the indicated frequency peak(s) on the screen displayed plot. Figure 8 illustrates an example of such a plot.

After selecting the mode and frequency of interest, the program then uses a direct computation of the discrete Fourier transform given by

$$F(\omega_k) = \Delta t \sum_{i=0}^{N-1} f(t_i) \left[\mathrm{Cos}\, \omega_k t_i - j\, \mathrm{Sin}\, \omega_k t_i \right]$$

where ω_k is the frequency of the mode to be analyzed, Δt is the data sampling interval, N is the number of data points in the block being transformed, t_i is the i^{th} time point, and j is $\sqrt{-1}$.

Since ω_k is an approximate frequency, procedures have been programmed to iterate to a nearly true ω by adjusting the harmonic number, k, and number of data points, N, used in the transform.

The next step in the method generates a time history of the function

$$G(\tau) = \ln \left| F(\omega_k) \right| , \quad t_1 \leqslant \tau \leqslant t_2$$

The time dependence of the function $G(\tau)$ is obtained by computing the function $\ln |F(\omega_k)|$ for a sequence of data blocks where $G(\tau)$ is computed by using the test data $f(t)$ for the time interval

$\tau \leqslant t \leqslant \tau + (N-1)\ \Delta t$; τ is the time of first data point in the block being transformed.

A running Fourier transform is used for computing efficiency. The data for each block is efficiently transformed by a recursive formula which uses the results from the previous block. After the first block, the result for subsequent blocks is obtained by a single deletion of a term, and the addition of a new term to the result of the previous block.

The basis for the peak plot method is that the transient response is closely approximated by an exponentially damped sinusoid. The actual peak plot is a plot of $\ln\ F\left|(\omega_k)\right|$ versus the time corresponding to the first data point for the sequence of data blocks. A measure of the damping is obtained by dividing the slope approximation of the plot by the frequency, ω_k.

Figure 9 presents a peak plot/time history display of a data sample representing a relatively highly damped control pulse response in the presence of noise and random excitation. The peak plot method has been used as an online procedure in some applications, but primarily as a postflight or posttest data analysis tool.

CONCLUDING REMARKS

Each of the flutter testing methods described has certain advantages and disadvantages such as cost, ease of use, specific excitation requirements, and applicability to specific test objectives and is used individually or in combination as judged necessary. None of the methods described provides conclusive stability data under certain flight conditions such as heavy Mach or transonic buffet conditions for higher damped modes. All methods described rely heavily on the engineer-in-the-loop approach for final judgement.

The availability of high-speed/capacity computers has provided the necessary tool for developing advanced data analysis methods which more fully satisfy the desired objectives of flutter testing at economically feasible levels. Current development studies within the aerospace industry and government agencies are contributing to more satisfactory solutions of the problem.

REFERENCES

1. Newman, K. W.; Skingle, C. W.; and Gaukroger, D. R.: The Development of Rapid - Testing Techniques for Flutter Experiments. C. P. No. 1274, 1974.

2. Soovere, Jaak; Turbulence Excited Frequency Domain Damping Measurement and Truncation Effects. NASA Symposium of Flutter Testing Techniques, Oct. 1975. (Paper No. 5 of this compilation.)

3. Mackenzie, Alexander: Application of the Fast Fourier Transform to Ground Vibration Testing, and Flight Flutter Testing. Proceedings of the Fifth Annual Symposium of The Society of Flight Test Engineers, Anaheim, California, August 7-9, 1974.

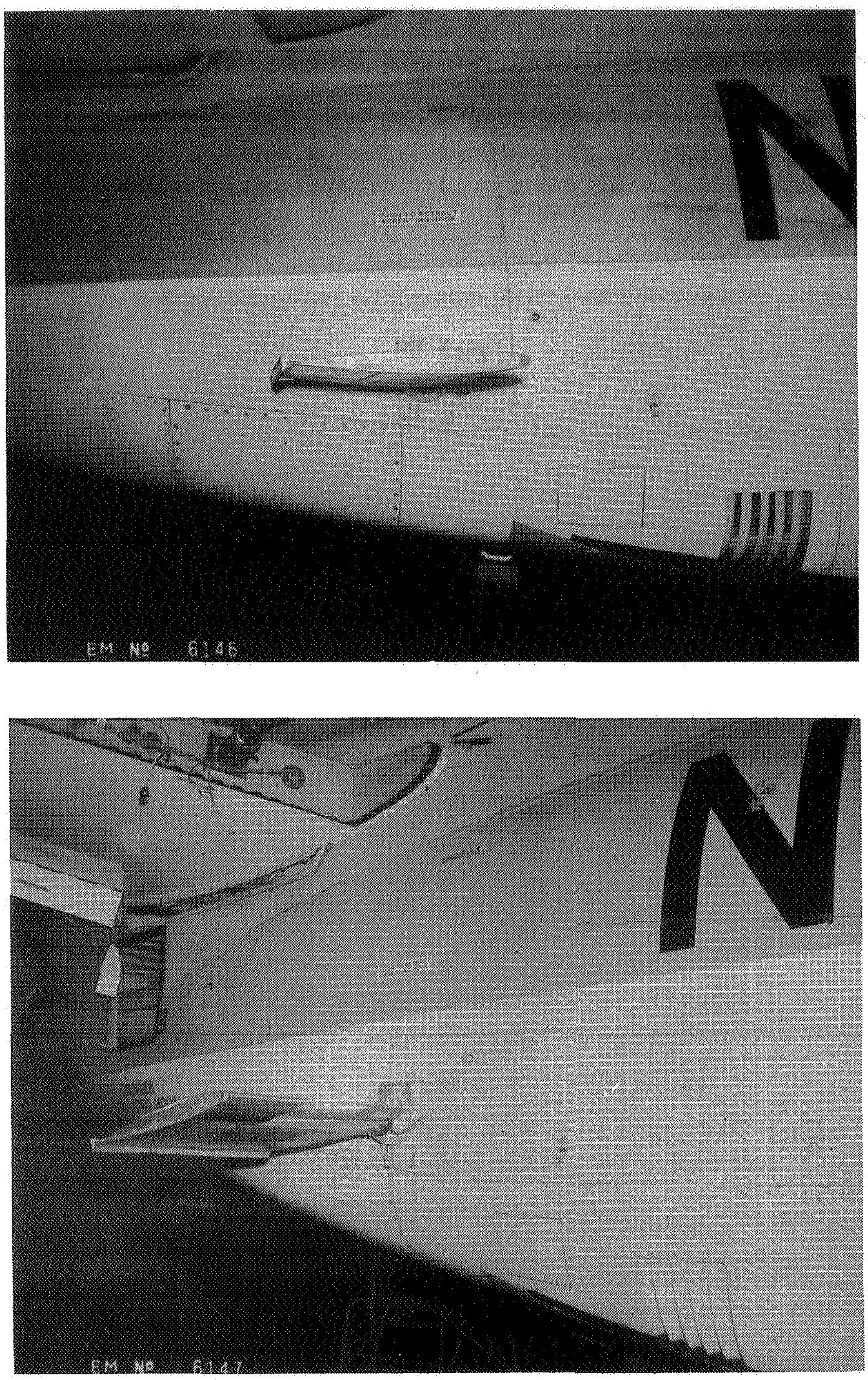
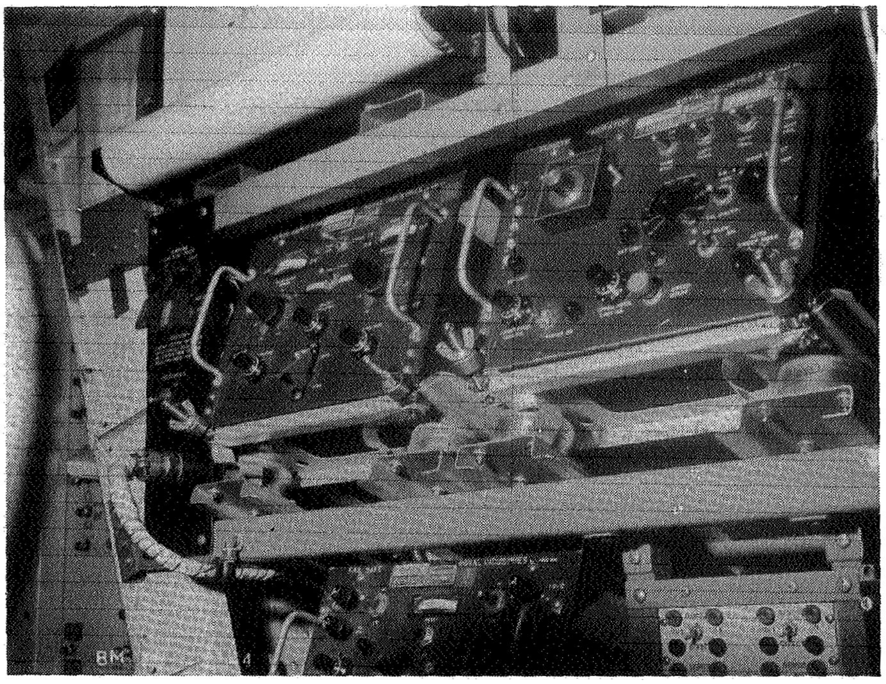


Figure 1. Photographs of flutter vane installed on aft fuselage.



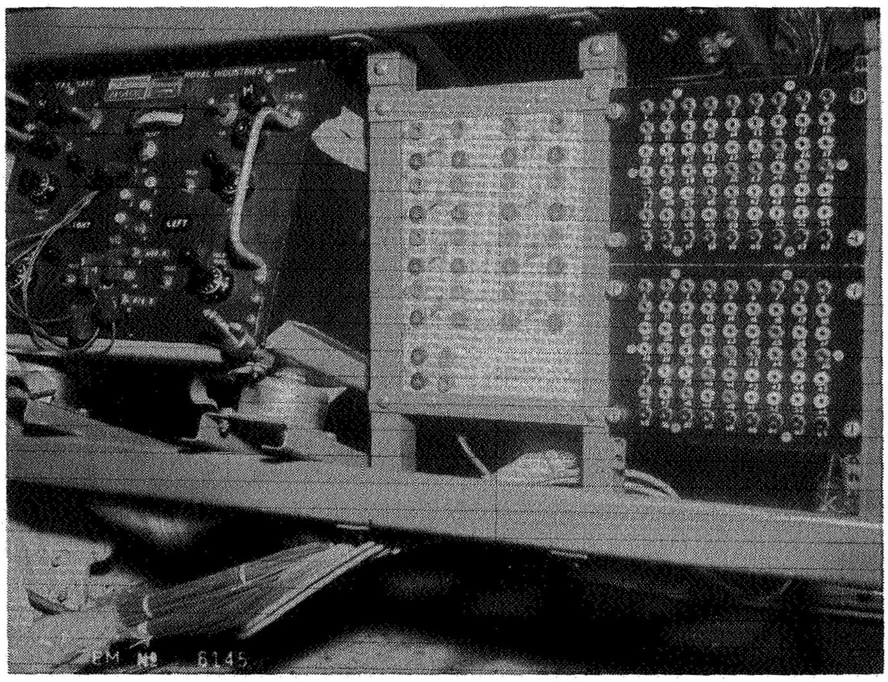


Figure 2. Photographs of the flight flutter test vane excitation control units.

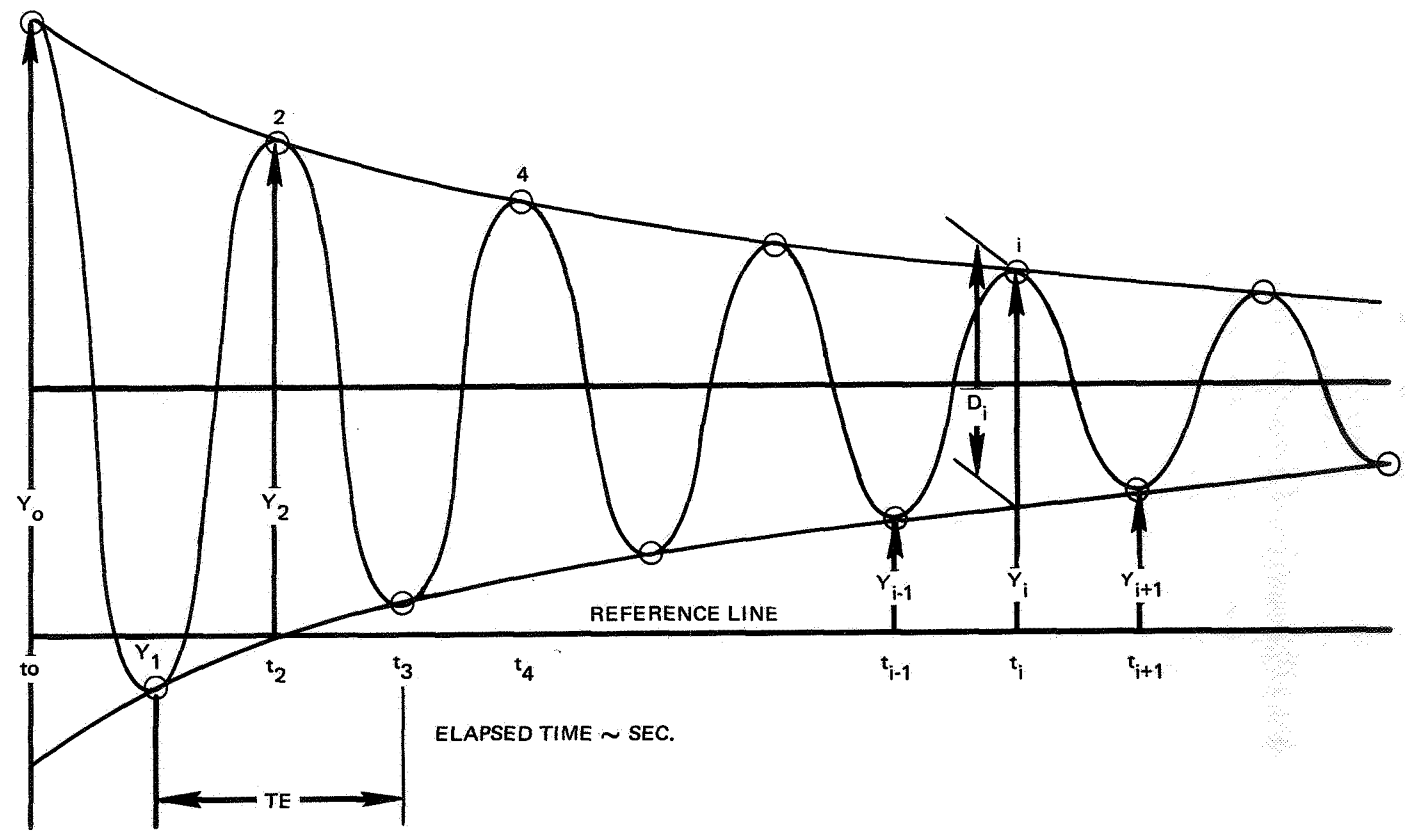
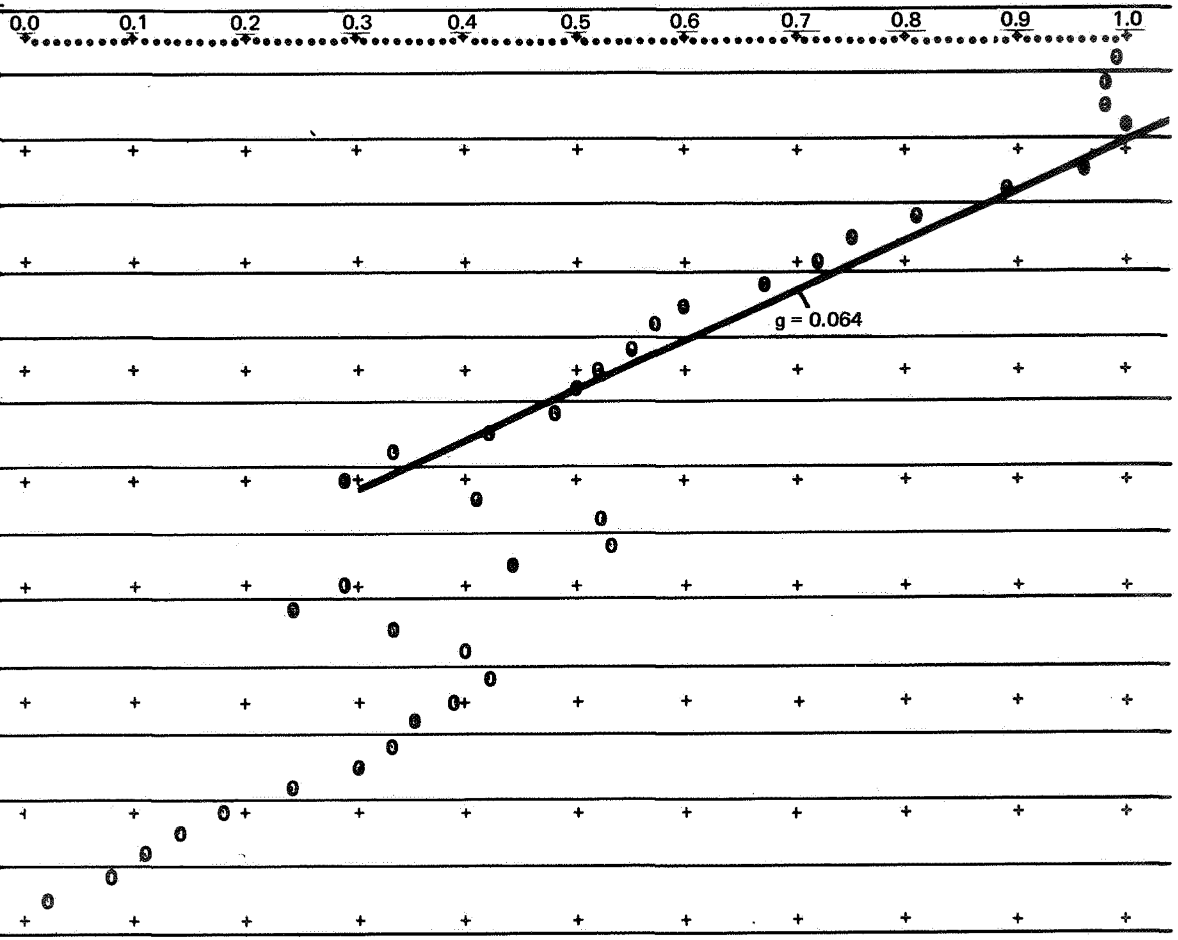


Figure 3. Real-time decay analysis time history assumed.

TEST 71 F 77 RUN 16 DATE 11-18-72 MODE 8
MEASUREMENT A3014 RT STAB T LON AC

START 12 HR 58 MIN 20.287 SEC IAS 369 KIAS HP 15100 FT MACH .7420 EAS 367

NO	TIME	FREQ	PEAK	AMPL
0	.158		2352	
1	.222	8.3	1731	612
2	.278	8.5	2335	596
3	.340	8.1	1747	600
4	.402	8.8	2360	626
5	.454	8.9	1722	623
6	.514	8.5	2331	570
7	.572	8.5	1800	481
8	.632	8.5	2232	400
9	.690	8.3	1865	355
10	.752	8.3	2209	331
11	.810	8.5	1892	290
12	.870	7.7	2155	249
13	.940	8.6	1921	233
14	.986	8.3	2154	223
15	1.060	7.8	1942	206
16	1.114	9.4	2143	200
17	1.166	9.4	1945	187
18	1.220	8.9	2121	164
19	1.278	8.6	1970	133
20	1.336	6.7	2086	121
21	1.428	6.7	1961	160
22	1.486	10.0	2156	207
23	1.528	10.0	1937	210
24	1.586	10.0	2138	174
25	1.628	6.7	1991	121
26	1.736	6.7	2087	108
27	1.778	11.4	1968	134
28	1.824	10.6	2118	158
29	1.872	10.4	1953	163
30	1.920	10.0	2115	154
31	1.972	10.0	1970	140
32	2.020	10.0	2105	133
33	2.072	9.6	1974	125
34	2.124	10.0	2093	109
35	2.172	8.9	1995	94
36	2.236	10.0	2085	86
37	2.272	11.4	2004	80
38	2.324	10.0	2083	76
39	2.372	12.5	2010	66
40	2.404	16.1	2070	50



M	S	g	E%	FM
17	4	.064	7.06	8.57

FE 08.0

1 FOOT = 0.3048 METER

LP 12 HP

TEST 71 F 77 RUN 16 DATE 11-18-72

Figure 4. Typical computer printout for real-time decay analysis.

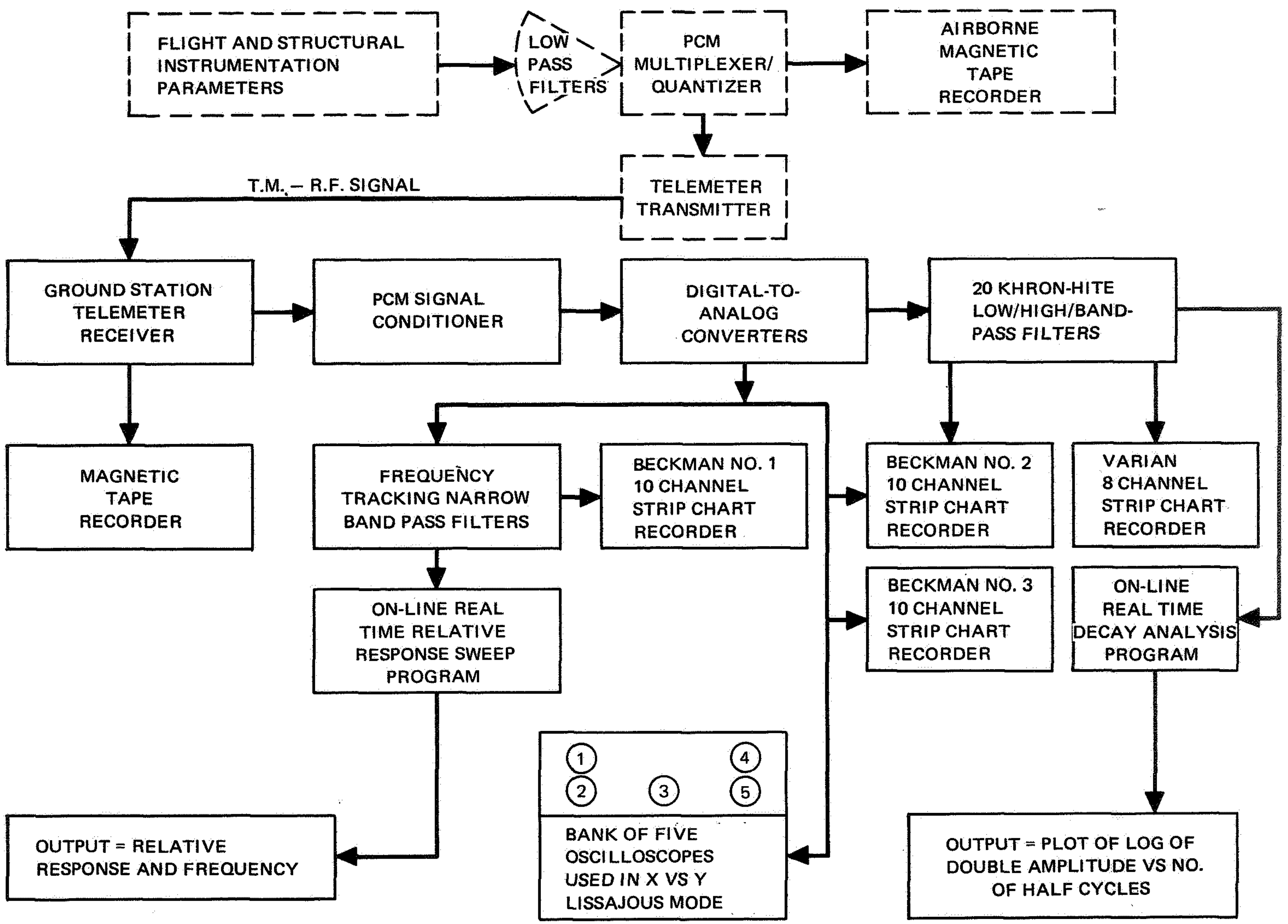
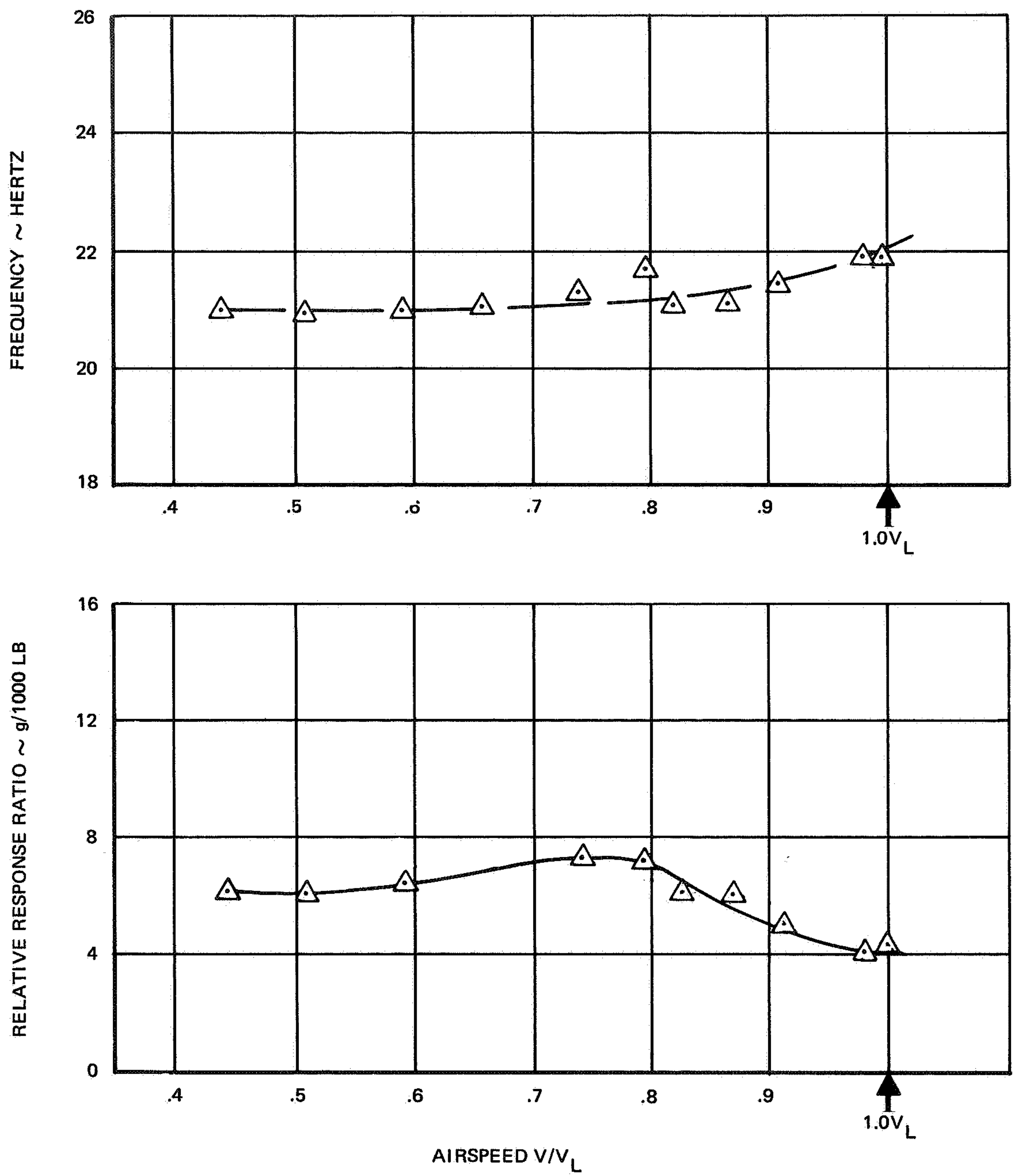


Figure 5. Typical flow chart of a PCM data acquisition/analysis/monitoring system.



1 POUND = 4.448 NEWTONS

Figure 6. Typical frequency and response ratio vs. equivalent airspeed from real-time response analysis.

TEST 73 F 82 RUN 6 DATE 321 ALT 8K KEAS. 420 M.74

FLIGHT FLUTTER TEST REAL TIME ANALYSIS

WINDOW = 20 EXCITATION WS+

MEASUREMENT A3013 RT STAB T VER AC

	HRS	MIN	SEC	KIAS	HP	MACH	KEAS
START	14	19	19.711	422	6170	.7220	426
STOP	14	19	41.122	424	5370	.7170	429

TIME AT INP PEAK SEC.	INPUT PERIOD SEC.	INPUT FREQ HZ	INPUT AMPLITUDE LB	RESPONSE AMPLITUDE G	RESPONSE RATIO g/LB X 10^{-3}
4.024	0.129	7.73	221.0	.20	.9
6.350	0.115	8.69	214.0	.54	2.5
7.302	0.109	9.14	208.0	.29	1.3
7.518	0.107	9.28	212.0	.51	2.4
7.840	0.105	9.46	211.0	.35	1.6
7.994	0.104	9.55	211.0	.67	3.1
8.204	0.103	9.67	210.0	.25	1.2
11.194	0.084	11.85	203.0	1.46	7.2
11.934	0.079	12.55	208.0	.12	.6
12.170	0.078	12.76	199.0	.62	3.1
12.518	0.075	13.21	200.0	.26	1.3
13.286	0.071	14.08	207.0	.93	4.5
13.672	0.068	14.63	205.0	.37	1.8
14.236	0.064	15.46	205.0	.54	2.6
14.366	0.064	15.54	206.0	.22	1.1
14.746	0.061	16.21	197.0	.33	1.7
18.912	0.035	28.30	224.0	.94	4.2
19.388	0.032	30.61	229.0	1.79	7.8
19.690	0.030	32.60	230.0	1.24	5.4
20.914	0.023	43.47	176.0	3.32	18.8

1 FOOT = 0.3048 METER

1 POUND = 4.448 NEWTONS

Figure 7. Typical computer printout for real-time response analysis.

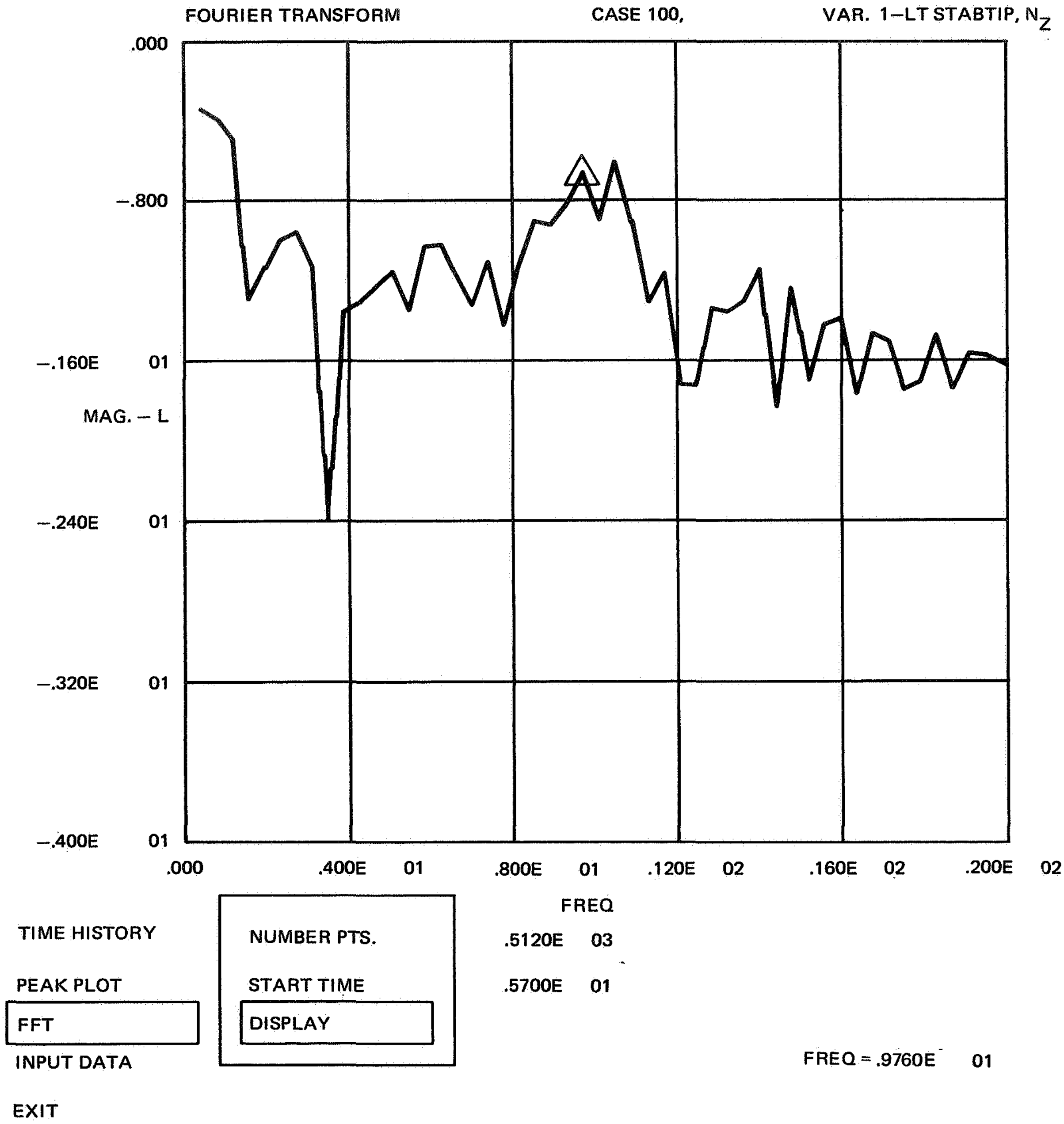


Figure 8. Typical Fourier transform display plot.

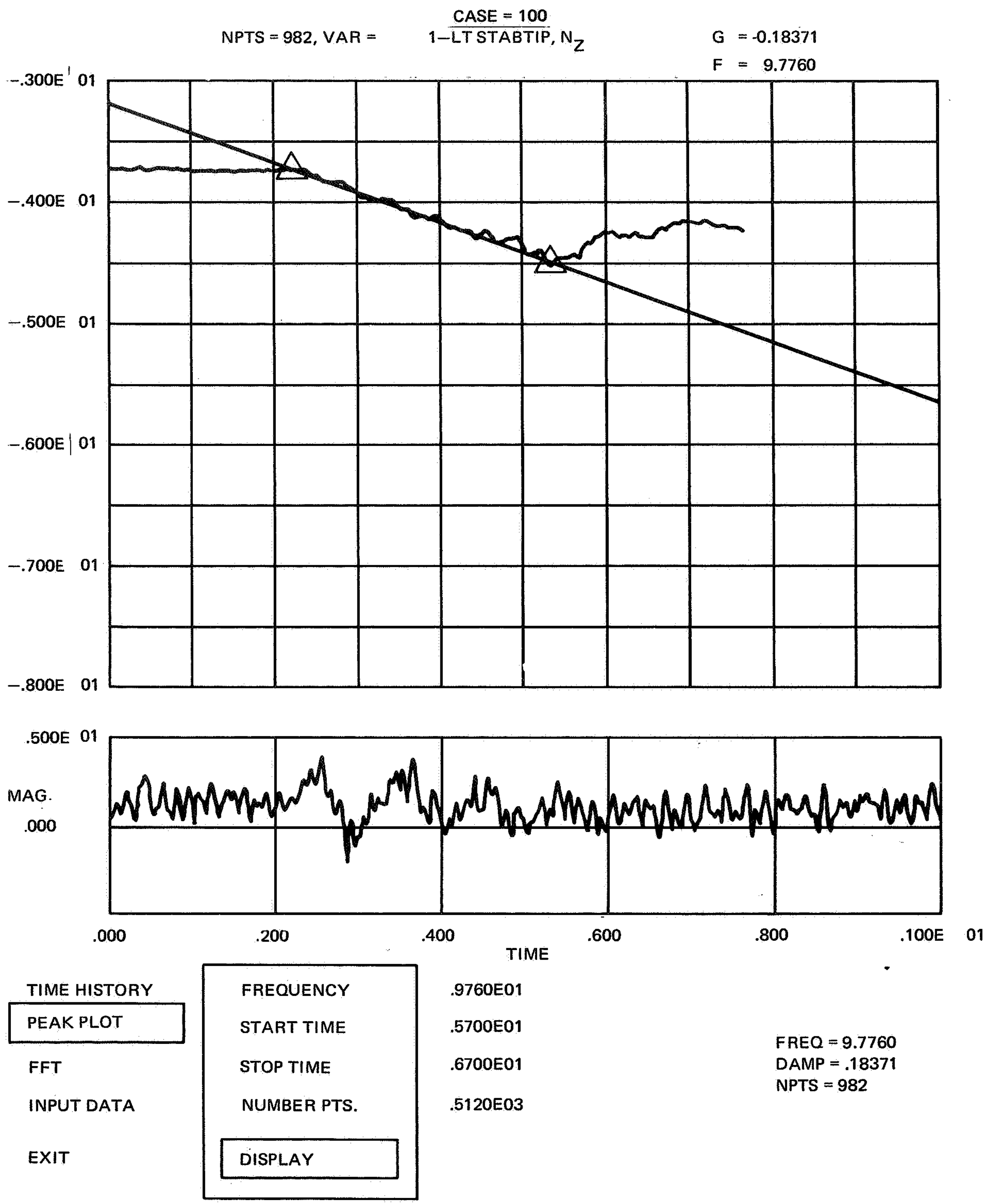


Figure 9. Typical peak plot display.