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AN IMPROVED METHOD OF MEASURING BLADE VIBRATION AND PREDICTING ENGINE DURABILIT

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NOTICE

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The work reported in this document seeks to establish the ability of an analytical model to predict the scatter in peak blade vibration amplitudes that occurs on bladed disk assemblies during tests of gas turbine engines. It then uses the resulting analytically generated statistics to investigate methods for selecting the number of blades that should be instrumented on a stage and methods for selecting which blades should be instrumented. In addition, it provides a method for calculating stage durability from the resulting test data. Keywords: Gas turbine blade vibration; Mathematical prediction;

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SUMMARY

The work reported in this document seeks to establish the ability of an analytical model to predict the scatter in peak blade vibration amplitudes that occurs on bladed disk assemblies during tests of gas turbine engines. It then uses the resulting analytically generated statistics to investigate methods for selecting the number of blades that should be instrumented on a stage and methods for selecting which blades should be instrumented. In addition it provides a method for calculating stage durability from the resulting test data.

FOREWORD

The work summarized in this report was performed by employees of Griffin Consulting and by employees of the subcontractor, Pratt and Whitney Aircraft. Essentially, all test data and model parameter inputs were provided by Pratt and Whitney Aircraft. The analytical simulations of bladed disk vibration discussed in this report were performed [illegible] Griffin Consulting. Opinions expressed in this report are those [illegible] Griffin Consulting and do not, necessarily, represent those of the subcontractor, Pratt and Whitney Aircraft.

This final report covers the entire contract period, 13 July 1984 to 30 September 1985. The work reported here was under the sponsorship of the AFWAL under the technical direction of Mr. William A. Stange.

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1. INTRODUCTION

This report presents the work conducted under the Air Force contract F33615-84-C-2454, "An Improved Method of Measuring Blade Vibration and Predicting Engine Durability." The objectives of the program were to improve procedures for instrumenting jet engines to measure blade vibrations and to improve the ability of engineers to predict engine durability. These goals are difficult to obtain because of "blade mistuning". Mistuning refers to small variations in the dynamic properties of the gas turbine engine blading that cause the blades to vibrate at slightly different frequencies and which can lead to large variations in resonant stresses from blade to blade. Since every blade in every engine cannot be instrumented, the issues are: which blades should be instrumented in a particular test engine to get the maximum amount of information, and how best to use this information to estimate the worst possible vibration that any engine of this type is likely to experience. The key to this problem is the use of mistuning statistics, a recent advance in structural dynamics, which seeks to bridge the gap between mistuning theory and its application in actual engines.

In mistuned rotors, individual blades behave in an almost unpredictable fashion. However, large groups of blades will always contain some blades that have small vibratory stresses, some that have large stresses, and many with stresses that lie in between. This statistical distribution of blade vibratory stresses is essentially the same for any large group of blades. It is the parameters that characterize this distribution which need to be substantiated during engine tests since it is the distribution of blade amplitudes which can be used to predict the response of the worst blade on the worst engine in the fleet and, consequently, predict the durability of the entire fleet.

Prior to the commencement of this program, computer programs had been written which predicted mistuning statistics for a given bladed disk assembly, Reference [1]. Since the underlying theory is linear, the programs could calculate the relative vibratory amplitude of blades on hundreds of disks and compile the resulting statistical distributions, but it could not predict their absolute magnitude because the magnitude of the excitation is not known a priori. It is the premise of work undertaken in this contract that the goal of vibratory testing should be to establish the absolute magnitude of the distribution and to check the validity of the underlying computer model. Then the computer generated statistics can be used to predict the worst blade behavior for the fleet. In addition, since the distribution of blade amplitudes can be compiled ahead of time, it can be used to optimize the placement of gages and to select the number of instrumented blades that are required to achieve a valid test.

The purpose of the research conducted in this program was twofold: to show that the statistical simulation program provides an accurate means of predicting amplitude scatter, and secondly, to illustrate how the statistical data generated by the computer program can be used to optimally instrument the stage.

The first purpose was to investigate how well the statistical simulation computer program predicts amplitude distributions. Prior to this research program the code had been used to generate a statistical distribution of blade amplitudes for one mode of vibration on only one bladed disk system. The results of that simulation were compared with test data in Reference [1]. The comparison proved satisfactory after the relatively large strain gage errors were taken into account (it was estimated that the old, hand-wound gages that were in use at that time measured strains accurately to within only plus or minus 50%). Consequently, one purpose of the work reported herein was to perform additional comparisons with test data. To that end it was necessary to establish an experimental data base of blade amplitude statistics, to characterize the accuracy of the measurements, and to perform baseline simulations of the vibrations in order to analytically predict the amplitude scatter.

The original study cited above, Reference [1], simulated the vibratory response of a high pressure turbine stage. Turbine blades are relatively stiff compared to the disk to which they are attached and significant amounts of mechanical coupling is transmitted through the disk. In the work performed in this program three modes of an unshrouded first fan stage bladed disk are simulated. Since for this stage the disk is extremely stiff relative to the blades, relatively little mechanical coupling takes place through the disk. Consequently, the comparisons of the predicted amplitude distributions with the experimental data made in this program provides three additional assessments of the validity of the statistical approach on a stage whose dynamic characteristics are quite different from that investigated in the original study, Reference [1].

A second purpose of the work performed in this program was to illustrate how statistical information about the blades' vibratory amplitudes could be used to optimally instrument a stage with strain gages. As was previously mentioned it is the view of this research program that the goal of measuring vibratory stresses during engine testing should be to establish the statistical distribution of blade amplitudes so that it can be used to predict stage durability. The distribution can be calculated analytically provided the magnitude of the generalized force acting on the bladed disk is known. Since the system is linear, the magnitude of the generalized force acts as a scaling factor which has the simple effect of proportionally increasing or decreasing the peak vibratory stress amplitude that each blade experiences. As a result, the mean stress on the stage is directly proportional to this quantity and, conversely, the value of the generalized force can be easily calculated if the mean stress on the stage is measured experimentally.

Several strategies for instrumenting the bladed disk are considered in this report. In each case the goal of the instrumentation is to characterize the distribution so as to infer the generalized force that acts on the stage. For example, in the first strategy N blades are instrumented on a random basis. The issue addressed in this program is how accurately can you assess the mean stress on the stage and how does this accuracy change as you increase the number of blades instrumented. As will be seen the answer to this question depends on the dynamic characteristics of the particular stage under consideration and, consequently, it is possible that one may find that five instrumented blades will be adequate for a first fan stage while ten blades must be instrumented to achieve the same level of accuracy for the second stage. Clearly, for a limited amount of instrumentation such an approach can be used to optimally distribute the available strain gages throughout the test engine.

The work is reported in this document in the following manner. Chapter 2 summarizes the input data required to develop the analytical computer model of the stage. Chapter 3 describes the analytical model, how the model parameters are calculated from the input data and summarizes the resulting values of the model parameters. Chapter 4 provides a summary of the engine test data. A comparison of the analytically predicted statistical distributions of blade amplitudes with engine data is given in Chapter 5. Chapter 6 deals with the results of the engine instrumentation optimization study, and Chapter 7 summarizes the main conclusions of the work.

2. INPUT DATA

In this chapter the data required to develop the analytical model of the stage's vibratory response will be summarized. The information that is required falls into four categories: The dynamic characteristics of a nominal blade, information about the nominal stage dynamics, statistical information which characterizes the blades frequency variation, and the amount of damping in the system.

The dynamic characteristics that will be used to establish nominal blade properties in the various modes under consideration are its "blade alone" modal mass and frequency in those modes (blade alone refers to how the blade would vibrate if it was attached to a rigid foundation). These properties for the first fan stage under consideration are summarized in Table 1 for the first three modes: 1st bending, 2nd bending, and 1st torsion. All nominal blade or system dynamic properties were calculated by the subcontractor using the NASTRAN finite element code. Blade alone mode shapes are depicted for these three modes in Figures 1, 2, and 3. Nominal properties will also be referred to as the "tuned" blade properties, i.e., the properties blades or system would have if it were machined perfectly to nominal specifications.

TABLE 1. BLADE ALONE PROPERTIES

Description	1st bending	2nd bending	1st torsion
Crossing	2E	4E	6E
rpm	6100	8700	7700
res. freq.	213.34	595.33	779.71
mod. mass	5.11 E-4	3.10 E-4	4.14 E-4

When a theoretically tuned bladed disk is excited, it responds in families of modes. For example, there is a first bending family in which the blades flex in a first bending type response and in which the disk may respond in various nodal diameter patterns. We will use the notation 1D, 2D, 3D, etc. to refer to the various nodal diameter modes in a family where the integer indicates the number of nodal diameters present. The frequencies of these families of modes are plotted in Figure 4 as a function of engine rpm. Note that the frequencies of the modes within a family are so close to each other in value that on this plot they appear as a single curve. This is due to the relative flexibility of the blades and the rigidity of the disk.

Each of these three families of modes will be excited in the running range by excitation sources whose frequencies are integer multiples of the engine rpm. We will employ the commonly used notation of 1E, 2E, 3E, etc. to indicate excitation sources whose frequencies are 1, 2, 3, etc. times the engine rpm. It can be shown that if the bladed disk were tuned that an N nodal diameter mode can be excited only by an N engine order excitation. From the Campbell plot of Figure 4 it is clear that the 1st bending mode family will be most strongly excited by a 2E excitation. If the stage were tuned it would only excite a 2D response in the disk. Thus, it is important to have a model which has approximately the same frequency response as the original system in the various nodal diameter modes. The procedure used here was to choose the values of the lumped spring mass system so as to match the tuned system response of the actual bladed disk in the primary response mode (2D for the case of a 2E excitation) and for a neighboring mode (1D in this case). One then finds that because of similarities in the physics of the systems the frequencies of the model system approximate those of the actual disk reasonably well over a range of nodal diameter responses. The 2nd bending and 1st torsion families of modes are dealt with in the same manner. The modal mass and frequencies of appropriate tuned bladed disk modes are summarized in Table 2.

TABLE 2: SYSTEM PROPERTIES

Lower ND	1	3	5
Freq.	210.18	589.43	774.29
Prim. ND	2	4	6
Freq.	212.91	592.66	776.61
Mod. mass	6.07 E-4	3.48 E-4	4.15 E-4
Higher ND	3	5	7
Freq.	213.16	593.88	777.32

Statistical data which characterize the variation in the blade frequencies are presented in Table 3. The values quoted are the frequencies of the blades measured during a shaker table test. In the statistical simulations it is assumed that the frequencies of the blades in the engine would vary by the same proportions from its nominal engine frequency. The mean frequency, standard deviation, and the ratio of the standard deviation to the mean for each blade mode are given in Table 4.

TABLE 3: BLADE FREQUENCIES

BLADE	S/N *	1ST MODE	2ND MODE	3RD MODE
1	1	166	489	793
2	2	166	495	797
3	3	167	490	802
4	4	166	495	801
5	8	165	492	796
6	10	167	498	806
7	11	167	493	807
8	12	167	494	801
9	14	167	496	799
10	15	168	494	806
11	20	169	495	804
12	24	168	496	804
13	25	165	493	798
14	26	168	494	802
15	27	165	495	795
16	29	169	499	810
17	30	167	490	805
18	31	167	496	803
19	32	167	496	799
20	34	167	492	801
21	36	169	500	802
22	37	168	498	809
23	39	167	496	801
24	42	166	493	800
25	43	167	495	798
26	47	167	491	796

*denotes blade serial number.

TABLE 4: IMPORTANT BLADE STATISTICS

Mode	1	2	3
Mean Frequency, f*	167	494	801
Standard Deviation, SD	1.1	2.8	4.3
Ratio, SD:f*	0.66%	0.57%	0.54%

The last system property that needs to be characterized is the damping. In Reference [1] it was assumed that all damping could be represented in the bladed disk model by a viscous damper from the tip of the blade to ground which contributed the same amount of modal damping to the system as that which was observed experimentally in the high response blades during the engine tests. The damping was inferred from the high response blades by considering tracking plots of their vibratory amplitude as a function of engine rpm and using the half-bandwidth method of calculating the damping ratio (the ratio of the amount of damping in the system to critical damping for that mode). The half-bandwidth method of calculating the damping ratio is equal to $d\omega/2\omega$, where $d\omega$ is the frequency change required to go from the half power point below the peak resonant response (the amplitude equals 70.7% of the peak value observed at resonance) to the half power point above peak resonant response and where ω equals the resonant frequency. Tracking plots for all the instrumented blades are given in Appendix A. Calculated values of the damping ratios observed on different high response blades are summarized in Table 5 along with their mean values. It will be the mean values of modal damping that will be used to calculate the viscous damping parameter in the analytical model.

TABLE 5: DAMPING MEASUREMENTS

Values of $\zeta = c/c_{critical}$ from high response blades, %

1st bending	2nd bending	1st torsion
1.6	1.2	0.7
1.5	1.4	1.3
1.1	1.1	1.3
0.8	0.8	1.0
		0.9
		1.2
		1.2
		0.9
		1.5
		1.5
		0.6
		0.9
ζ_{ave} = 1.2,	1.1,	1.1

The above approach for characterizing the system damping was successful in Reference [1] but was found to be inadequate for the stage studied in this program. One reason for this is that the unsteady aerodynamic forces including the aerodynamic coupling terms are far more important for a large flexible fan blade than they are for a turbine blade. As a result, during this program it was necessary to modify the dynamic spring mass model in order to incorporate aerodynamic coupling terms. The various aerodynamic force terms are either in phase or 90 degrees out of phase with the relative motions that occur between the blades and essentially contribute either a dynamic stiffness or damping to the system. There are six stiffness and damping parameters that were introduced into the model in order to characterize aerodynamic forces between each blade and the gases that flow arround it and between each blade and its neighboring blades. The values of these parameters were calculated for the three modes of interest using a computer program which incorporated the NASA developed aerodynamic code, RAO, Reference [2]. The computer program can calculate the unsteady aerodynamic forces provided that the modal displacements correspond to either simple bending or simple rotational motions, but not both. Upon consideration of the mode shapes associated with the first three modes, it is apparent that first two modes are predominately bending whereas the third mode (which we have been calling 1st torsion) has significant components of both bending and rotation. In order to run the aerodynamic code the modal displacements of all three modes were simplified as consisting of either simple bending motions (for the first two modes) or a simple torsion type rotational motion in the case of the third mode. The resulting errors in the mode shape were judged to be most significant for the third mode. The aerodynamic coefficients that resulted from these calculations are summarized in Table 6. Their relevance to the mass spring system representing the bladed disk is discussed in Chapter 3.

TABLE 6: AERODYNAMIC COEFFICIENTS

Coefficient	1st bending	2nd bending	1st torsion
K21	7.3	4.0	-108.
K22	-7.5	-28.0	-344.
K23	-2.5	10.3	12.
C21	0.0026	0.0037	0.0459
C22	0.0190	0.0205	0.3548
C23	0.0024	-0.0028	-0.076

Note that the computer program for calculating the aerodynamic coefficients, Appendix B, was developed by Griffin Consulting and sent to the subcontractor, Pratt and Whitney Aircraft, in order for them to calculate the aerodynamic coefficients. The input data describing the flow conditions in the engine (Mach number, gas density, etc.) are not available for general distribution and, consequently, are not contained in this report.

3. THE ANALYTICAL MODEL

In this chapter the procedures used to establish the nominal values of the model's parameters will be discussed first. Then, the basis for incorporating the statistical variations will be given.

The analysis used in computing the blades' amplitudes is based on establishing the vibratory response of the spring mass system depicted in Figure 5. Note that the parallel lines in Figure 5 indicate beamlike elements which have zero extensional flexibility and transverse stiffnesses as noted. The model used here differs from that used in Reference [1] in two respects. Only one mass (instead of two) is used to represent the blade's degree of freedom. This was shown to be an adequate representation in Reference [3] and simplifies the modelling process. Secondly, stiffnesses and damping elements were added in order to better represent the aerodynamic forces in the system. These correspond to the additional springs and dashpots labelled K21, K22, K23, C21, and C23 in Figure 5.

The external force represents a particular engine order excitation and, as a result, is sinusoidal in time and differs only in phase from blade to blade. This type of excitation is caused by circumferential variations in the flow field which translate into a source of periodic excitations in the reference frame of the rotating blades. The resulting forcing function is equivalent to a Fourier series which has frequencies proportional to integer multiples of the engine rpm. As the engine changes speed, one of these frequencies will coincide with a natural frequency of the bladed disk at which time the other terms in the Fourier series have little effect and are negligible. Under these circumstances each blade is exposed to the same excitation except for differences in phase which are proportional to the blade's circumferential position on the disk. The cases simulated are of this type, for example, the 1st bending mode is subjected to a 2E excitation at approximately 6000 rpm (Figure 4) and in that case the phase difference between the excitation acting on neighboring blades is equal to 4π divided by the number of blades, 26. The amplitudes and phase difference between neighboring blades are summarized for the excitation in Table 7.

TABLE 7: EXCITATION CHARACTERISTICS

MODE	1st BENDING(1)	2nd BENDING(2)	1st TORSION(3)
Engine Order	2E	4E	6E
Magnitude of Excitation	1.0	1.0	1.0
Phase Difference (Radians)	2π/13	4π/13	6π/13

In this study, the analytical simulations attempt to represent actual components as tested in an engine configuration. Consequently, the mean values of the model's parameters are selected to represent the nominal physical system as closely as possible. In the actual rotor the dominant resonant response corresponded to a specific blade mode stimulated by a particular engine order excitation, say nE. Thus, to simulate this response properly it was important to do two things: 1) Let the blade-part of the model have the same modal response as the actual blade; and 2) in order to get the right amount of interaction between the mistuned modes and the nE excitation, have the circumferential response of the bladed disk model be the same as that of the actual hardware.

Originally, it was assumed that these physical constraints could be satisfied in the same manner as used in Reference [1]. The following description summarizes that approach. The mass and stiffness of the blade elements, m2 and K2, are chosen so that the nominal blade model has the same modal mass and frequency as the actual blade in the blade alone mode of interest (refer to Table 1 for specific values as calculated via the finite element method). Secondly, that the disk's lumped mass and spring parameters are chosen so that the modal mass and resonant frequency of the spring mass system are the same as that of the nominal bladed disk in the nth nodal diameter mode (which means that the nominal spring mass model would predict the same amplitude of response for an nE excitation as would a finite element analysis of the bladed disk). Lastly, the disk's circumferential stiffness parameter, K6, is chosen so that the next lower nodal diameter mode in the spring mass system has the same frequency as that calculated by the finite element analysis. (In fact, this means that all of the adjacent nodal diameter modes have approximately the correct frequencies).

It is clear that such an approach satisfies requirements 1) and 2) stated above. It also satisfies the requirement that the number of constraints equals the number of degrees of freedom in the model and, hence, provides a mechanism for uniquely establishing all of the nominal values of the masses and stiffnesses used in the model. This approach proved completely successful in simulating the turbine disk of Reference [1]. However, if the mass spring model of Figure 5 is examined more closely it shows that, in addition to the modes of vibration just discussed, there is a second family of bladed disk modes in the radial direction having various circumferential nodal lines, 0R,1R 2R, etc., that correspond to additional radial bladed disk modes. (This phenomenon occurs in all two dimensional structures; for example, if a circular disk is vibrated its modes of vibration can have radial, as well as diametral nodal lines. Because of circular symmetry, the spring, mass system used in this simulation also has this property. The families of modes under discussion have zero and one circumferential nodal lines. The mode having one circumferential nodel line - the 2nd radial mode - is spurious). In the case of the turbine stage, Reference [1], the second radial mode was also present but occurred at a significantly higher frequency than that of the mode under consideration and, consequently, had no effect on the analysis. In the case of the fan stage under investigation in this program the second radial mode of the spring, mass system is very close to the mode of interest and, consequently, its presence would strongly effect the dynamic response analytically predicted by the model. It has been verified that this result cannot be changed by using two masses to represent the blade if the blade's modal mass is constrained to be the same as that of the physical blade. It has also been verified that this is a spurious effect caused by the limitations of the lumped parameter system and that it does not occur in this manner in the actual physical system that we wish to simulate. The presence of the spurious mode follows from the physical constraints that we have applied and the model we have selected and occurs in this instance because of the relatively massive disk to which the blades are attached. The only way of removing this unwanted mode from the frequency range of interest is to relax one of the constraints used in establishing the model's parameters.

The least important constraint is that the mass representing the blade in the model has the same value as m_{ba}, the modal mass of the blade in its blade alone mode of response (i.e. when its attached to a rigid foundation). A parametric study was conducted to ascertain the effect of m_{ba} on the frequency of the second radial mode. This was performed computationally by varying μ, the mass ratio between the blade and disk (m3/m2). Once a modal mass is established which gets the second radial mode out of the frequency range of interest it is then necessary to calculate the new values of the lumped masses and springs which satisfy the other sytem constraints. It was found that the frequency of the second radial mode was quite high and, as a result, out of the frequency range of interest for low values of μ and that it deceased as μ increased until for large values of μ its frequency was very close to the first radial mode. Thus, in this respect lower values of μ were more desirable. However, when low values of μ were used no physically acceptable values of the system parameters could be found which would satisfy the other system constraints. For this reason, moderate values of μ were chosen which resulted in acceptably high second radial mode frequencies and, also, physically meaningful values of the model parameters.

As an example of this, consider the two nodal diameter, 1st bending mode. The mode we wish to simulate has a frequency of 212.9 Hz. and using the original modelling technique the spurious 2nd radial mode has a frequency of 214.4 Hz. By letting the blade alone modal mass change from 0.00051 to 0.00061 the frequency of the spurious mode is increased to 398 Hz., well out of the range of the simulation. This approach was used for each of the modes and the resulting values of the masses and springs used in the final simulations are given in Table 8.

TABLE 8: NOMINAL VALUES OF MASSES, SPRINGS & HALF-BANDWIDTH DAMPING

Parameter	1st bend.	2nd bend.	1st torsion
m_1	6.05 E-7	3.46 E-7	4.12 E-7
m_2	6.05 E-4	3.46 E-4	4.12 E-4
m_3	3.03 E-2	1.75 E-2	4.12 E-2
k_1	1.09 E+6	4.85 E+6	9.90 E+6
k_2	1.09 E+3	4.85 E+3	9.90 E+3
k_3	9,259	6.48 E+4	1.91 E+5
k_6	1.37 E+6	8.27 E+5	1.16 E+6
C22*	0.019	0.029	0.045

The nominal damping parameters were calculated in two ways. The first method that was used in Reference [1] was to let all of the system damping be incorporated into viscous dampers that act between the tip mass on each blade and ground (the ground represents the gas). The main source of damping in bladed disks is usually due to aerodynamic effects. Consequently, the underlying assumptions in this approach are that interblade aerodynamic coupling is negligible and that the aerodynamic damping can be inferred from half-bandwidth estimates of damping calculated from strain gage tracking plots of the high response blades. (See Chapter 2 for additional discussions concerning this approach). Using this approach one may calculate the damping ratio for the mode and, using values of modal mass and frequency, calculate the corresponding values of C22 to be used in the models. Values of C22 calculated in this manner are given in Table 8 as C22*.

A difficulty that can occur with this approach is that mistuned stages can have multiple peaks which can coalesce and make the half-bandwidth estimating method unreliable (typically it will overestimate the damping). A second problem is that the method of incorporating damping into the model fails to take into account aerodynamic coupling between the blades which is an especially important effect in large, flexible fan blades. To compensate for these difficulties a second, analytical approach was developed to assess aerodynamic effects which used the NASA developed code RAO, Reference [2], to calculate aerodynamic coupling terms. Since the aerodynamic forces are linearly proportional to the displacements and velocities of the blades it was possible to calculate values of equivalent springs and dashpots that would exert the same forces on the stage as those predicted aerodynamically. The dampers and springs associated with the aerodynamic effects are labelled K21, K22, K23, C21, C22, and C23 in Figure 5. Their values as calculated using the aerodynamic code are given in Table 6.

There are two distinct statistical aspects of the problem that need to be characterized experimentally: the variation in the natural frequencies of the blades, and strain gage measurement errors.

The natural frequencies of the blades were measured in the modes of interest using a shaker table. Their values are given in Table 3. Since these are developmental blades, a larger sample size is not available to better characterize frequency variations. It is assumed for purposes of this study that the observed frequency variations in the test blade sample would be representative of those that would occur in production. (This assumption would have to be verified by tests on additional blades once the engine was in production if the stage proved sensitive to mistuning). In addition, it is assumed that the percent variation in blade frequencies would be the same in the engine as on the shaker table. For example, in the shaker table test the mean frequency of the blades in first bending was 167 Hz. and the standard deviation was 1.1 Hz. or 0.66% of the mean value. Under engine conditions the first bending frequency increases to 213 Hz. because of centrifugal stiffening and it is assumed that the standard deviation in the frequency would be 1.4 Hz. (which is 0.66% of 213 Hz.). This assumption allows us to take engine effects on blade frequency into account in our simulation. The key blade frequency statistical data is summarized in Table 4. Note that the ratio of the standard deviation to the mean is approximately constant, 0.6%, for all three modes.

Strain gage measurement errors where estimated using laboratory tests in which ten different blades were instrumented with engine size gages and shaken at three different amplitudes in the modes of interests. The original test data sheets are provided in Appendix B, the statistical results are summarized in Table 9 in which a key result is ρ, the standard deviation in the strain measurements as a percentage of the average value measured. The data is given for strain gages located on the blades in various physical locations which were designated by the subcontractor as locations E1, E2, ..., etc. These locations are indicated in Figure 6. Note that only pertinent statistics are given in Table 9, for example, for the first bending mode, statistics for gages in positions E1 and E5 are given only since gages in the other locations were not adequately sensitive to this mode of vibration and were not used to measure its response. This information will be used during the simulation in order to facilitate the comparison of the analytical predictions with the test data in the following manner.

TABLE 9: STRAIN GAGE ERROR SUMMARY
Measured at constant tip amplitude of 0.090 inches

Quanity	E1	E2	E4	E5	E6
1st bending mode					
Ave strain	5.3			2.1	
Stand. Dev.	0.43			0.06	
ρ	8.1%			3.0%	
2nd bending mode					
Ave strain	11.9				
Stand. Dev.	0.90				
ρ	7.6%				
1st torsion mode					
Ave strain		10.3	17.7		9.4
Stand. Dev.		1.3	2.1		0.5
ρ		13%	12%		5%

First, the statistical amplitude variations due to mistuning will be computed. Then each data point will be reprocessed under the assumption that it is subjected to a random, log normal strain gage error whose mean value is one and whose standard deviation is a specified percentage of the value measured. The distribution in strain gage errors is assumed to be log normally distributed in order for the simulation to always result in positive definite amplitude distributions for large samples, which, of course, is a physical constraint which must be met, i.e. you always measure positive amplitudes.

This completes the description of the nominal and statistical models.

4. ESTABLISH VIBRATORY STRESS AMPLITUDES FROM ENGINE TRACKING PLOTS.

In this chapter the procedure for establishing the strain gage amplitude distribution from the engine test data will be given. Experimental amplitude distributions will be summarized.

A typical engine tracking plot is given in Figure 7. The strain gage under consideration is located at a position on the blade that is sensitive to the 1st and 2nd bending modes. These modes are excited by Fourier components of the excitation whose frequencies are proportional to two and four times the engine rpm. Thus, the 1st bending response may be established by using a 2E filter (the middle plot) which is synchronized with two times the engine's rpm. The peak 1st bending response for this strain gage may be read from the 2E filtered plot as 5.8 KSI. Similarly, the 2nd bending mode response is given by the top plot as 3.9 KSI.

Two engine tests were conducted during which the blades' vibratory responses were measured, one in Hartford and one in Florida. The tracking plots for both sets of tests are given in Appendix A. An example of how the data was processed is indicated in Table 10.

The case considered in Table 10 is the Hartford data for the 1st bending mode. First, the peak values of all the vibratory stresses are read from the 2E filtered tracking plots. Strain gages 130 and 131 were located at a different position on the blade from the rest of the gages so their stress values had to be multiplied by the appropriate modal ratio (2.5) in order to establish equivalent stress values for these two gages. The mean value of the stresses was then calculated for this set of equivalent stresses to be 5.1 and the equivalent stress data was then normalized by this value. The stresses were then ordered by their magnitude and assigned a probability rank. The probability rank in percent was calculated using the formula

P = 100 x (2i - 1)/N

where i is the order of the observation and N is the total number of observations.

TABLE 10: EXAMPLE OF DATA PROCESSING: 1ST BENDING

Hartford data:

SG#	SG Loc	Stress	Eq. Stress	Normalized
104	1	5.5	5.5	1.08
105	1	6.5	6.5	1.27
106	1	5.8	5.8	1.14
130	5	1.5	3.8	0.74
131	5	1.5	3.8	0.74
		mean =	5.1	

Order	Rank	Value
1	10%	0.74
2	30%	0.74
3	50%	1.08
4	70%	1.14
5	90%	1.27

5. COMPARISON OF ENGINE DATA WITH PREDICTIONS FROM THE ANALYTICAL MODELS AND AN EXAMPLE OF A DURABILITY PREDICTION.

First, the experimental data will be compared with those predicted analytically when the simple aerodynamic model based on one damping parameter and half-bandwidth measurements from tracking plots are used. Then the experimental data will be compared with scatter predicted using the aerodynamic parameters calculated analytically utilizing RAO.

A description of how the experimental data was processed is provided in Chapter 4. In the case of the analytical data, the peak amplitudes were calculated for each blade on the disk and a strain gage error, representative of those observed in the laboratory tests, was statistically incorporated into its final "measured" value of stress. The amplitudes were then listed and processed in an identical manner to the experimental data.

The comparisons between the experimental data and analytically predicted values that were calculated using the simple aerodynamic model are made graphically in Figures 8, 9, and 10. Figure 8, which displays the results for the 1st bending mode, is representative of the results for all three modes. Note that the analytical model underpredicts the amplitude scatter observed in the engine by a significant margin. For example, one would predict that the worst amplitude one would expect to see on a disk would be 30% higher than the average value observed. In fact, the engine data indicated that it was closer to 90%. In summary, the simple approach did not predict the amplitude scatter observed in the engine well. (It should be pointed out that the Hartford and Florida data have been treated as independent observations in this comparison and have been lumped together after they were normalized by their respective mean values. The conclusion would be essentially the same if data from the two engines were compiled separately).

It was felt that the model may have underpredicted the amount of scatter because the half-bandwidth method of estimating damping tends to overestimate its actual value. This occurs because mistuning results in multiple peaks that can coalesce and provide the appearance of a broader single peak. In the turbine disk that was previously analyzed, Reference [1], it was felt that this was not a significant problem since all of the high response blades exhibited about the same amount of damping. That was not the case in the fan stage considered in this study. In this investigation the damping varied significantly more from blade to blade and, as a result, it was not clear what the best value of damping would be to use in the model. Damping values were calculated analytically to compensate for this uncertainty and the mistuning model augmented so that it could incorporate the additional aerodynamic terms that represent coupling between the blades. As was mentioned in Chapter 3, the third blade mode (which has been casually referred to as the 1st torsion mode in this report) was the hardest to model aerodynamically because it corresponded to the most complex mode shape of the three modes that were modelled. In the third mode each section of the blade had significant bending components as well as rotations. The aerodynamic code could simulate either a simple section translation or a simple rotation, but not both concurrently. As a result, for the third mode, the bending component of its motion was deleted and its behavior modelled as simple torsion.

The resulting analysis predicted that larger values of aerodynamic damping should occur than were measured experimentally using the half band-width approach. Since the half-bandwidth method overestimates damping it was felt that the aerodynamic coefficients for the 3rd mode were significantly in error, probably due to the aforementioned simplifications required in representing its mode shape.

The comparison between the experimental data and values predicted analytically is depicted for the 1st bending mode in Figures 11a and 11b. In the first figure the Florida and Hartford test data are processed separately. Both sets of data agree well with the analytical predictions. The Florida data would agree even better if there were not one data point with an exceptionally high value. The data points at the extremes of the probability spectrum are the least reliably known. Consequently, this disagreement with one observation is not particularly disconcerting. Note that its presence significantly affects the mean of the distribution and because of the normalization procedure shifts all of the other amplitudes observed in this test to the left. Thus, the important point is that while the data are slightly shifted to the left (relative to the analytically predicted trend), the slopes are essentially the same. In Fig 11b the test data from the two tests have been combined into one probability distribution. Under this approach the effect of the single large value is less pronounced and the good agreement between the experimental and analytical data is more apparent.

Comparisons are made for the 2nd bending mode in Figures 12a and 12b. The comparison with the Hartford data is quite good although the data is limited (there are only 3 data points). The comparison with the Florida data is at first glance not as good until we observe that this is due in large part to a single datum which appears to be atypical. In this case the value of the peak stress was unusually small, 0.05 of the mean value (note that the next smallest values were an order of magnitude larger) and one might suspect an experimental error of some type. In fact, this strain gage had an unusual tracking plot in that it had no apparent 2E response at all and only a very marginal 4E response (see tracking plots in Appendix A). For this reason this datum was considered of questionable validity and the engine data was analyzed a second time without its value being incorporated into the process. The results are depicted in Figures 13a and 13b. With the removal of the outlying data point, the agreement of the engine data with the results predicted by the analytical model is judged to be excellent.

The results for the 3rd mode are depicted in Figures 14a and 14b. There is poor agreement between results predicted analytically and those observed experimentally. It is believed that this poor agreement is due to errors in the aerodynamic coefficients caused by a poor representation of the relatively complex motions that occur in this higher mode.

To provide an example of how durability predictions could be made for this stage, the response of the first bending mode was analyzed using a large simulation of 200 bladed disks. The resulting probabiltiy distribution of amplitudes is depicted in Figure 15. The worst stress that one should observe in 500 disks (based on extrapolation of the data) is approximately 1.5 times higher than the mean stress. The mean stress in the Hartford test was 5.1 KSI peak to peak. This implies that the maximum stress one would expect to see in 500 engines tested under comparable run conditions would be 7.7 KSI, well below the vibratory limit for this blade. It is clear that an important issue is how well do we know the mean stress for the distribution. This is addressed in the next chapter on instrumentation procedures.

In conclusion, it is noted that for the first two modes considered, the scatter in the amplitudes of vibratory response was predicted quite well by the analytical model utilizing the NASA developed aerodynamic code, RAO. Consequently, relative amplitude scatter can be computed in these cases completely analytically before the engine test is run and the resulting statistics used in establishing an instrumentation strategy. Several approaches to instrumenting the engine are discussed in the next chapter.

6. INSTRUMENTATION OPTIMIZATION STUDY

6.1 INTRODUCTION

This chapter deals with using the statistical information on how the stage vibrates to instrument the engine. Two goals of engine testing are: 1) establishing the statistical distribution of amplitudes, and 2) protecting the stage so that it lasts through the test program without losing a blade because of excessive vibrations. With the approach used here the first goal can be achieved by establishing the distribution's scale. This can be done by experimentally determining the mean, median, or any other characteristic measure of the amplitudes since this establishes f_o, the magnitude of the excitation, in our analytical model. The second goal can be accomplished in several ways: either indirectly by knowing the ratio of the worst stress on the stage to its mean value and monitoring the mean stress during the experiment, or directly by trying to instrument the blade that will vibrate most strongly on the engine disk.

These goals of measuring the mean stress on the stage and monitoring the worst blade on the engine test disk provides our criteria of how well a particular instrumentation strategy works. That is, if there is a limited number of gages that can be used on a stage, how big is our error when we try to estimate a characteristic stress (such as the mean stress, or the maximum stress on the stage) from our measurements when a particular strategy is used in selecting the blades that are to be instrumented.

Two primary strategies will be examined: selecting blades randomly, and selecting blades to instrument based on their blade alone frequency. A third strategy which will be briefly considered for establishing the magnitude of the excitation, f_o, will consist of modelling the test engine stage and trying to find a value of f_o which gives the best correlation of the experiment with the analytical model.

In the following sections these instrumentation strategies will be illustrated by investigating how they could be applied to the 1st bending mode.

6.2 RANDOMLY SELECTING BLADES

The key attribute of randomly selecting the blades to instrument is that it provides an unbiased sample of the distribution of blade amplitudes and that, consequently, the mean value of the vibratory stress that is observed is always an estimate of the mean value of the distribution, a result which is truly independent of the number of blades instrumented. The issue then becomes one of how well can the mean value of the distribution be determined from the mean value of the stresses that are measured. A measure of error in this situation is the standard deviation that is observed when making an estimate of the mean from a limited sample since one would expect the estimate to be accurate to within plus or minus two or three standard deviations depending on the confidence level sought. Estimating the mean of a distribution from a limited randomly selected sample is a classical problem in statistics and according to the Central Limit Theorem, Reference [4], the standard deviation predicted in estimating the mean is equal to the standard deviation of the statistical distribution that is sampled divided by the square root of N, where N is the number of blades instrumented.

This classical result was tested numerically by considering ten disks in which each disk had N randomly selected instrumented blades. The mean vibratory amplitude was calculated for each disk with N equal to 2, 4, 6, etc. and the standard deviation in the means calculated from the resulting ten values. The results are depicted in Figure 16 along with the theoretical results one would calculate using the Central Limit Theorem and the fact that the standard deviation of the ten disk sample was 10.8% of the mean. The numerical data agrees reasonably well with the theoretically predicted behavior and it is clear that the Central Limit Theorem could be used directly once the standard deviation of the overall distribution is known.

The results in Figure 16 can be used to select the number of gages that should be used on the stage in order to achieve a specified level of accuracy in estimating the mean. Alternatively, it is apparent that there is a significant improvement in the accuracy of the estimate if the number of gages is increased from 2 to 6 or 8. Conversely, it would not seem worthwhile to have more than 8 gages unless there were exceptional circumstances. This result depends on the level of mistuning in the stage and on a number of physical factors which can be different with each mode and stage considered. The overall instrumentation strategy for an engine can be established once curves of this type are developed for all the stages. One might find that a given level of accuracy can be achieved in all the stages if, for example, 8 gages are used in the first stage, 6 in the second, and 10 in the third stage.

Randomly instrumenting the blades is appealing because it is an easy strategy to implement, requires no additional analysis beyond a baseline mistuning analysis to calculate the standard deviation, and provides and unbiased estimate of the distribution. It does not provide a very effective method of instrumenting the high response blades. To do that we need to recognize the relationship that exists between the frequency of individual blades and the amplitudes they tend to exhibit in the mistuned bladed disk. Then we may preferentially instrument those blades which tend to be the high responding blades. This approach is addressed in the next section.

6.3 CHOOSING BLADES BY THEIR FREQUENCIES

The first question addressed in this section is whether or not there is a correlation between the blade alone frequency of a blade and how it vibrates on the disk. In Reference [1] it was found that blades whose frequencies were close to the tuned system frequency tended to act as tuned absorbers and, on the average, tended to be the high response blades in the system. To establish if this was also the case for the fan disk considered in this research program, the peak amplitudes of the fan blades were plotted as a function of their blade alone frequencies in Figures 17 and 18 for the 1st and 2nd bending modes, respectively. In each case approximately two hundred amplitudes were generated analytically and plotted as open triangles. In both plots there is a tendency for blades with frequencies near the tuned system frequency (the solid vertical line) to vibrate most strongly. Thus, it can be concluded that the same type of dependency on blade alone frequency is predicted for the fan blade modes as was observed in the earlier study of turbine blades, Reference [1]. The experimental data from the engine test was also plotted (as the solid squares) in Figures 17 and 18 as a check on the analytical predictions. The amplitudes of the test data were scaled so that they had the same mean value as the analytically generated data and their frequencies by scaling the blades bench test frequencies so that they had the same mean frequency as the blades in the analytical model. The trends in both sets of experimental data tend to confirm the distribution predicted by the analytical model. Note that in this instance the analytical data was not processed to include strain gage error while, of course, the engine data included this additional source of error. Consequently, while the experimental data shows the same overall trends as that predicted analytically, it also exhibited more scatter than expected based on the analytical results.

In summary, both the analytical and experimental data confirmed that the blades with frequencies near the tuned system frequencies of the bladed disk tended to be the high response blades. This result suggests the instrumentation strategy of instrumenting those blades with blade alone frequencies nearest this tuned system frequency. Such a strategy results in a biased sample and, as a result, the mean amplitude measured, A^*, is not the mean of the overall distribution. Furthermore, the mean value measured depends on the number of blades instrumented. Thus, two issues need to be addressed in this section with regard to A^*: 1) how does the average stress measured on one engine with N blades instrumented relate to the mean stress of the overall distribution from many engines of this type, and 2) what is the uncertainty in A^* in such a measurement.

The purpose of adopting a strategy of instrumenting blades preferentially by their blade alone frequency is, of course, to improve the chances of monitoring the stresses on the worst blade on the disk. How well this goal is met is assessed by determining the "max amplitude ratio", R, as a function of N, the number of gages on the disk. R is the ratio of the maximum amplitude measured to the amplitude of the maximum responding blade on the disk. When R is equal to 1.0, the maximum peak amplitude on the disk has been measured. If it is known that on the average R is 0.9 for the instrumentation strategy, then the maximun stress you observe is multiplied by 1.11 in order to estimate the worst stress on the disk. A second concern is how much uncertainty there is in R. Clearly, as the number of gages is increased, R goes to 1.0 and there is less uncertainty involved in whether or not you have measured a value nearly equal to the worst stress. This uncertainty may be assessed by knowing the standard deviation in R as a function of N, the number of blades instrumented.

Thus, four quantities will be assessed in this study as functions of N: 1). A*, the mean amplitude of the sample, 2) β, the standard deviation in A* as a percentage of A*, 3) R, the max amplitude ratio, and 4) SDR, the standard deviation in R. These quantities were be calculated using a 50 disk simulation in which N blades are instrumented preferentially by their frequency. For example, when N equals two, two blades on each disk were chosen with frequencies closest to some prescribed value, and A* and R were calculated for the 50 bladed disks simulated. From these 50 samples standard deviations for A* and R were determined. Thus, A*, R and their standard deviations are known for N equal to 2. This process was repeated for other values of N and the results depicted as plots of A*, R, etc. as functions of N.

Three approaches will be assessed: instrumenting blades with frequencies nearest the tuned system frquency, instrumenting the lowest frequency blades, and instrumenting the highest frequency blades. The results are depicted in Figures 19 through 22. First, consider how A* and its standard deviation depends on N for each of these approaches.

A* is plotted as functions of N for the three instrumentation approaches in Fig 19. The results are reasonable if Figure 17 is taken into consideration in that if blades are instrumented near the tuned system frequency they tend to be the most highly responding blades; if the lowest frequency blades are instrumented, they tend to have somewhat above average response (the overall mean is about 0.051); and, if the high frequency blades are instrumented, the blades have below average response. The values plotted in Figure 19 are important in that they allow you to convert from the mean amplitude value that you measure to the mean amplitude of the overall distribution. Note that A* depends on N and must be calculated analytically using this type of simulation technique. Figure 20 yields the standard deviation in A* as a function of N. It is clear that instrumenting high frequency blades results in consistently higher measurement errors than the other two approaches. Instrumenting low frequency blades and instrumenting blades near the tuned system frequency results in comparable errors in measuring A* except for very low values of N at which time instrumenting the low frequency blades results in a better estimate of A*.

The maximum amplitude ratio, R, is depicted in Figure 21. Once again it is clear that instrumenting blades with frequencies near the tuned system frequency results in a better chance of measuring the high response blade since R is consistently higher using this approach. The uncertainty in R is proportional to its standard deviation which is depicted in Figure 22. Again instrumenting the high frequency blades produces the most uncertainty in the measurements, whereas, the other two approaches have lower and comparable uncertainties.

From these plots, one might conclude, for example, that it is best to instrument the eight blades on this disk with frequencies nearest the tuned system frequency, i.e. those blades having bench test frequencies 0.2% below the mean bench frequency of all the blades on the disk. In this case the average amplitude measured is 1.02 times the mean amplitude of all blades of this type with an uncertainty of approximately plus or minus 12% (3 standard deviations). In addition, the worst stress measured on any of these eight blades is 97% of the highest stress on any of the blades on the disk also with an uncertainty of plus or minus 12%.

6.4 PREDICTING THE RESPONSE OF THE TEST ENGINE

A third strategy for calibrating the analytical model and determining the magnitude of the excitation, f_0, is to predict the response of the specific bladed disk system used on the test engine and choose f_0 so as to provide the best correlation with the engine data. This is not an instrumentation strategy so much as a way of establishing a scale factor for the distribution in order to perform a durability calculation. To test this approach the response of the test disk was simulated as closely as possible and the resulting peak amplitudes correlated with those observed experimentally. The results are depicted in Figure 23. Note that the experimental results are scaled so as to have the same mean response as the analytical values. A perfect correlation would lie on a straight line with a slope of 45 degrees. After some consideration of this plot it is apparent that there is no significant correlation between predicted and experimentally measured values of peak amplitude. Consequently, it was concluded that this was not a feasible approach for estimating f_0.

Several comments should be made concerning this result. Firstly, this was never considered a very attractive approach because there was no way to access the uncertainty in f_0, whereas the other approaches provide a method for estimating the error in how well we know the mean stress (and hence, f_0). Secondly, it has been shown that very small modelling errors can result in very large errors in how we would predict a particular blade on the disk would vibrate, however, such errors do not significantly affect the overall statistical response of the bladed disk system, Reference [2]. This is why the statistical approach is needed to circumvent the unreliability that is inherent in a deterministic approach. Thus, in conclusion, Figure 23 indicates the strong need for a statistical approach to this class of problems.

7. CONCLUSIONS AND RECOMMENDATIONS

The following observations and conclusions are made with regard to the work that was carried out during this project:

1. The approach for modelling the bladed disk system had to be modified in two respects from that used in Reference [1] in order to provide an adequate representation of the physical system. The first difference is that the parameter identification constraint (which stipulated that the mass of the blade part of the spring-mass model had to be the same as the modal mass of the blade in its blade alone mode of response) had to be relaxed. This was necessary in order to move a spurious second radial system mode of the spring-mass model out of the frequency range of interest. This difficulty occurred in all three modes of the fan blade but did not occur in the previous turbine stage simulation, Reference [1]. This difference between the turbine and fan stages is attributed to the increased stiffness of the disk relative to the blades in the case of the fan. (The stiffness of the disk is indicated by the fact that the bladed disk frequency was only 0.2% less than the blade alone frequency for the fan stage while it was 2% less for the turbine stage.) It is believed that this change in modelling technique will be required in any situation involving very stiff disks and flexible blades.

The second difference was that an improved aerodynamic model had to be used in order to properly compute blade scatter. The aerodynamic model used in the spring-mass system was improved by including additional spring and dashpot elements which represented aerodynamic forces between blades. The coefficients of these elements were computed analytically utilizing the NASA developed aerodynamic code RAO. It was concluded that the aerodynamic coefficients calculated for the third mode (also referred to as the 1st torsion mode) were significantly in error. This is attributed to the significant simplifications that were required in modelling the mode shape of this higher order mode in order to represent it as a simple torsion motion for input to RAO.

2. The augmented mistuning computer code correctly predicted the

statistical distribution of blade amplitudes in the first two modes, 1st and 2nd bending. This was indicated by good agreement with engine test data on amplitude probability plots and on correlations of amplitude with bench test frequency. The code did not correlate well with the 3rd mode's response. This difficulty is attributed to difficulties in calculating the correct amount of aerodynamic damping in the system for this complex mode. For the first two modes the approach offers a completely analytical method of computing relative amplitude scatter, and, as a result, can be used to optimize instrumentation strategies prior to testing.

3. None of the modes studied would cause a durability problem.

4. The instrumentation optimization study was completed. It considered how to select the number of gages that should be used on the stage and which blades should be instrumented. Choosing blades randomly is appealing because it results in an unbiased sample and requires less analysis to implement. However, if blades are chosen by their bench test frequencies there is a higher probability of measuring the high response blades on the test engine and preventing blade loss. This approach results in a biased sample which must be accounted for analytically in interpreting the resulting data and projecting engine durability. In summary, using mistuning statistics to select an instrumentation scheme can result in safer tests and better data with less error.

The following recommendations for additional work are made:

1. In order for mistuning statistics to be a useful tool for the design and test engineer it has to be put in a "package" which is easier to use. To this end it is recommended that a user friendly computer package be developed with integrated graphics so that the key results can be quickly and easily viewed by the user.

2. It is important that additional work be done on understanding various sources of errors that can occur in measuring vibrations during engine testing. This study included work on strain gage error due to gage

placement and geometric variations in the blade. Additional sources of error are encountered during actual testing that need to be better understood and characterized statistically.

3. Additional work should be done to better understand the response of the fan stage investigated in this study. There is a considerable amount of engine data available on the response of the blades in 1st torsion. The mode should be reanalyzed for its mistuned response after an improved aerodynamic model has been used to calculate better aerodynamic coefficients. Then, if the predictions of amplitude scatter compare well with the engine test data, it will be established that the problem with the 3rd mode was, in fact, due to a poor aerodynamic model and not due to some other limitation of the lumped parameter representation. In addition, another engine test of this fan stage is currently planned. It would be worthwhile to process the strain gage data from those tests to provide an additional comparison with the analytical predictions made during this study.

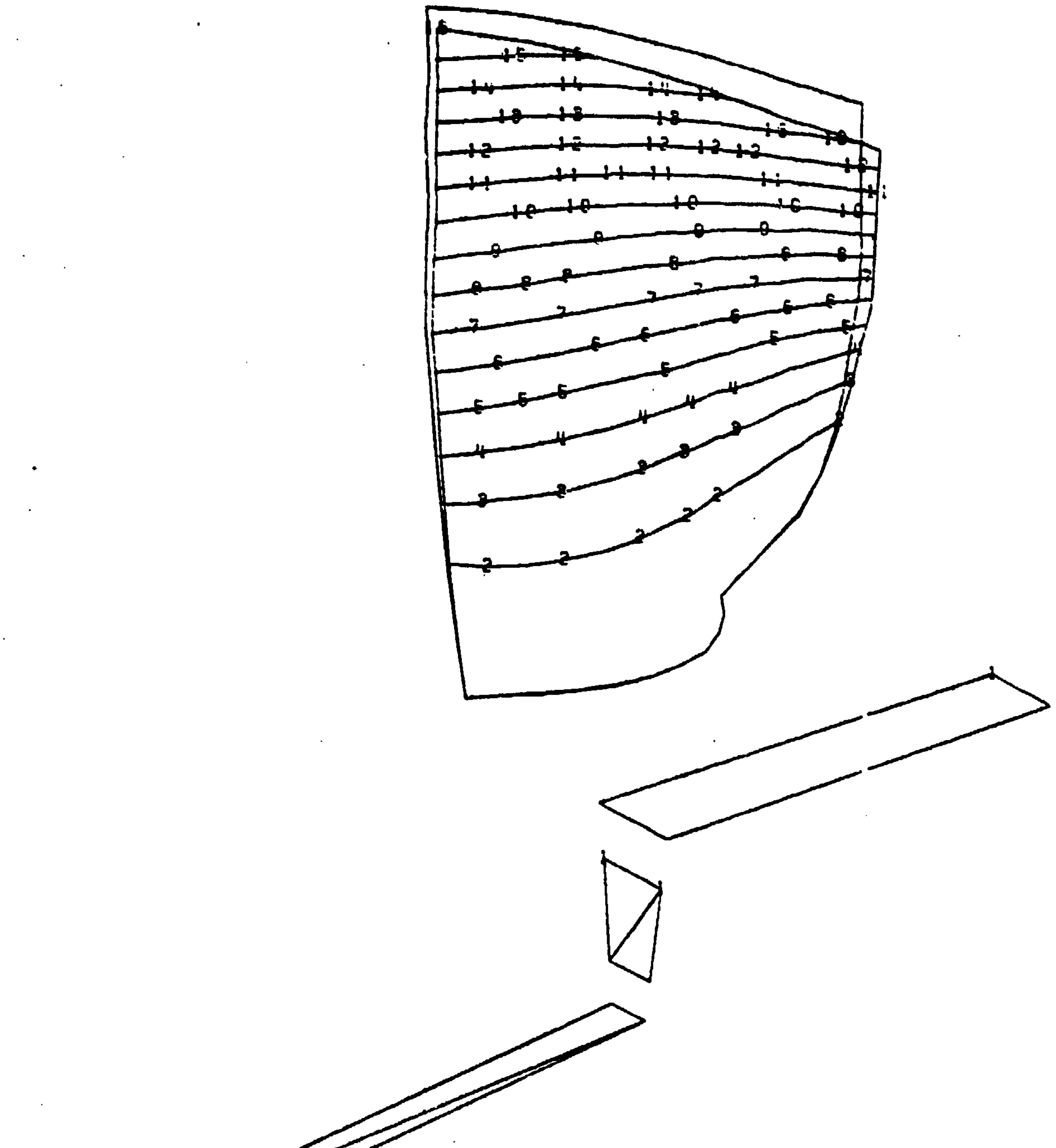


FIG. 1. FIRST BENDING MODE

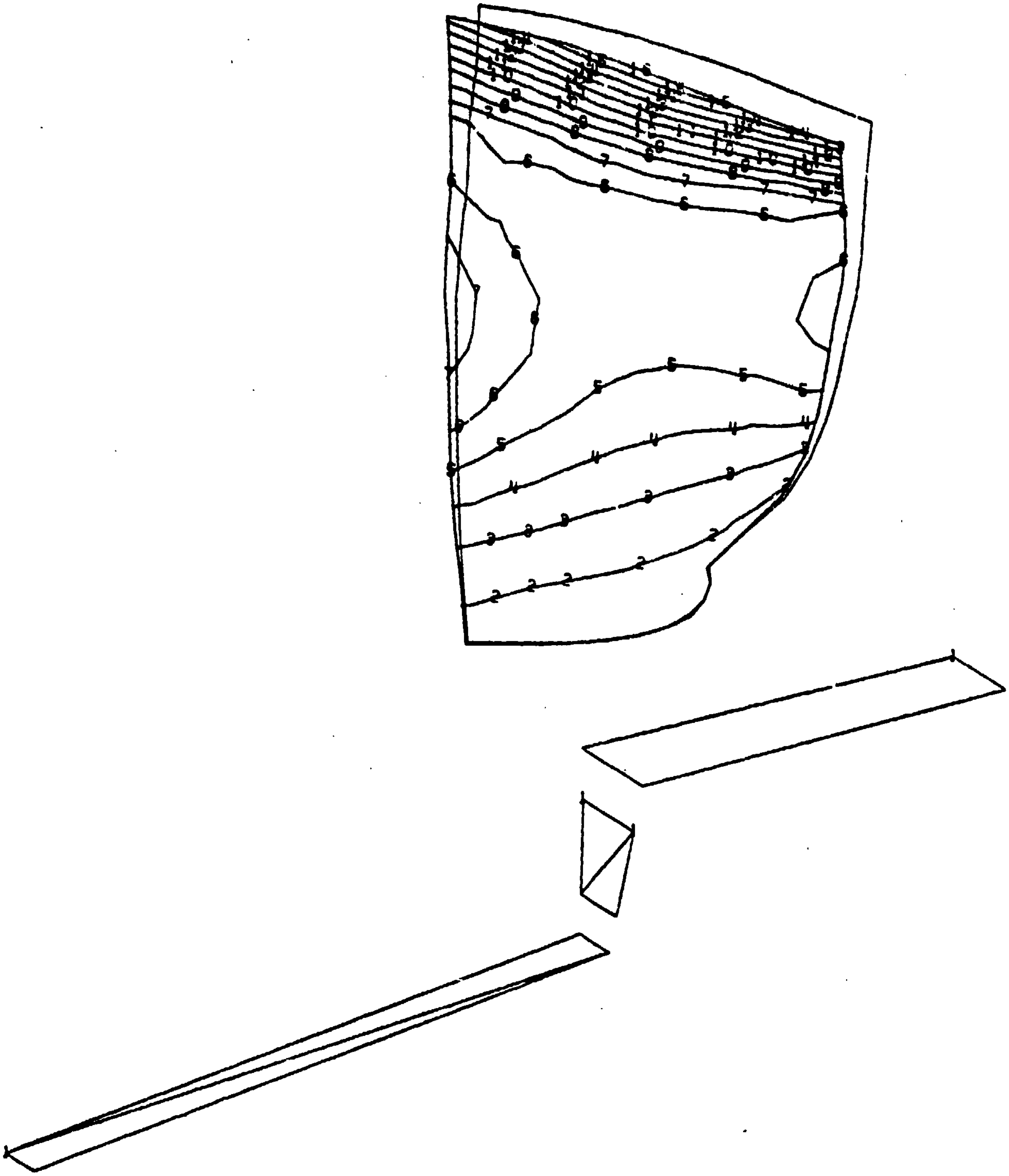


FIG. 2.   SECOND BENDING MODE

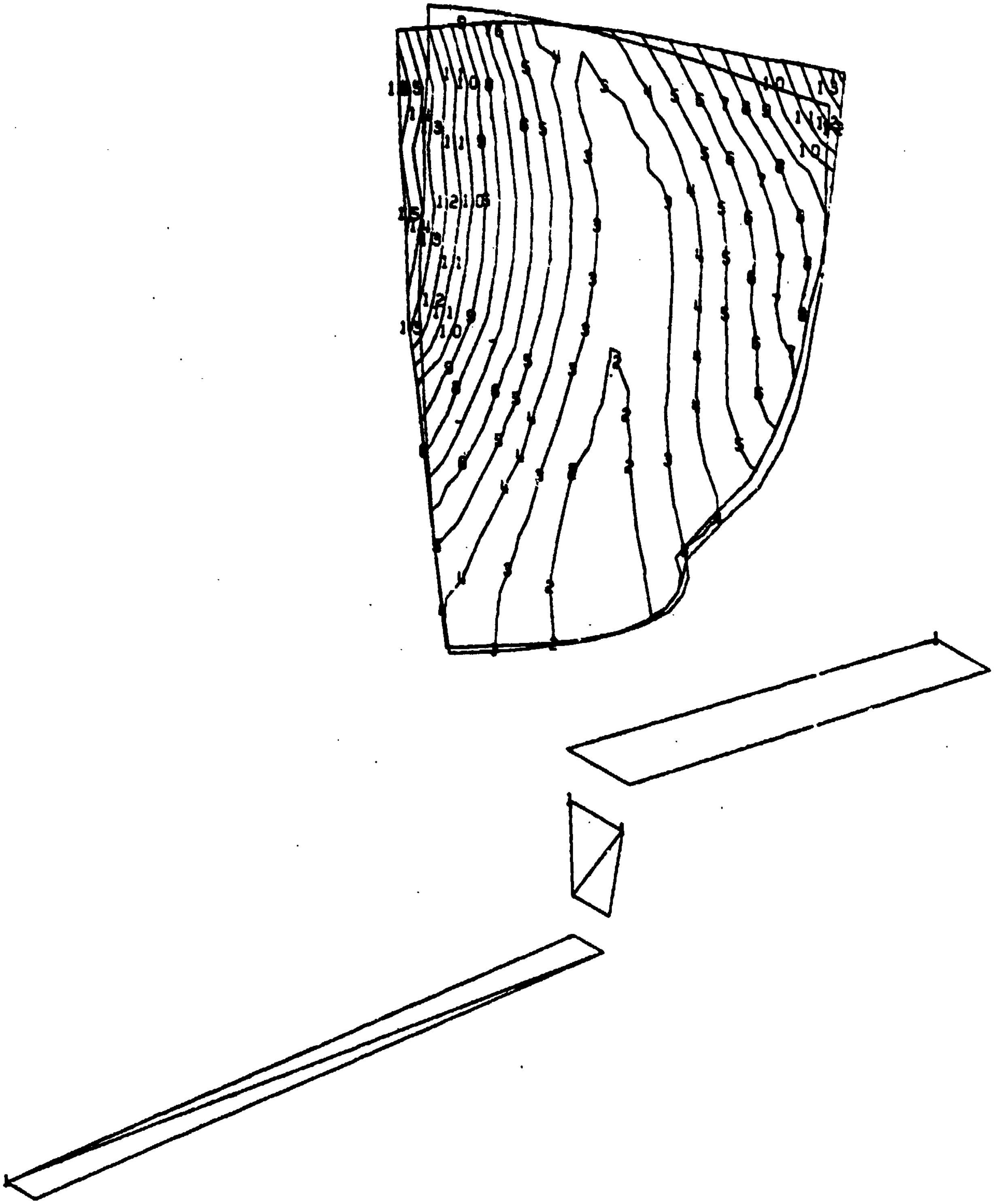


FIG. 3. FIRST TORSION MODE

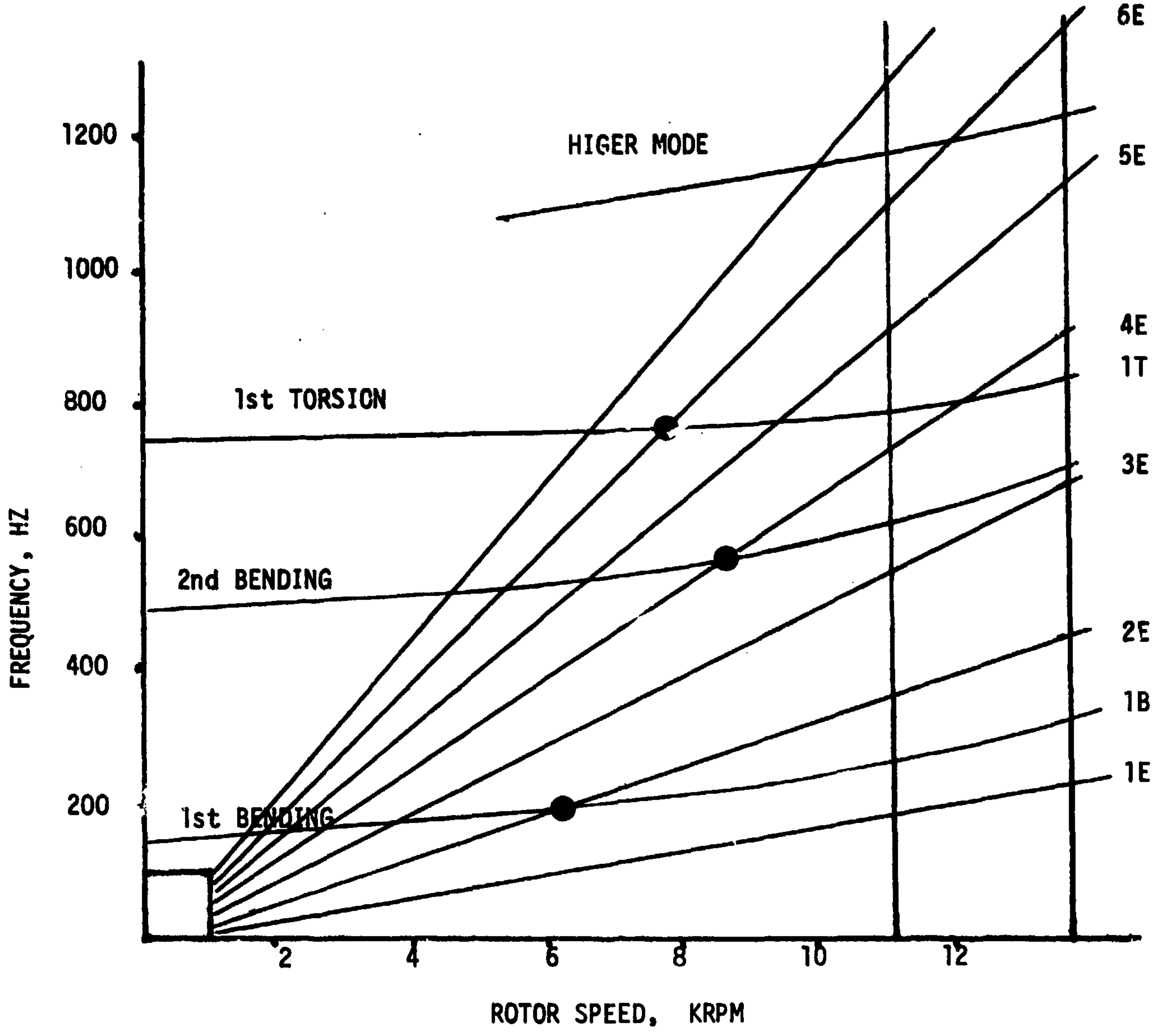


FIG. 4. CAMPBELL PLOT

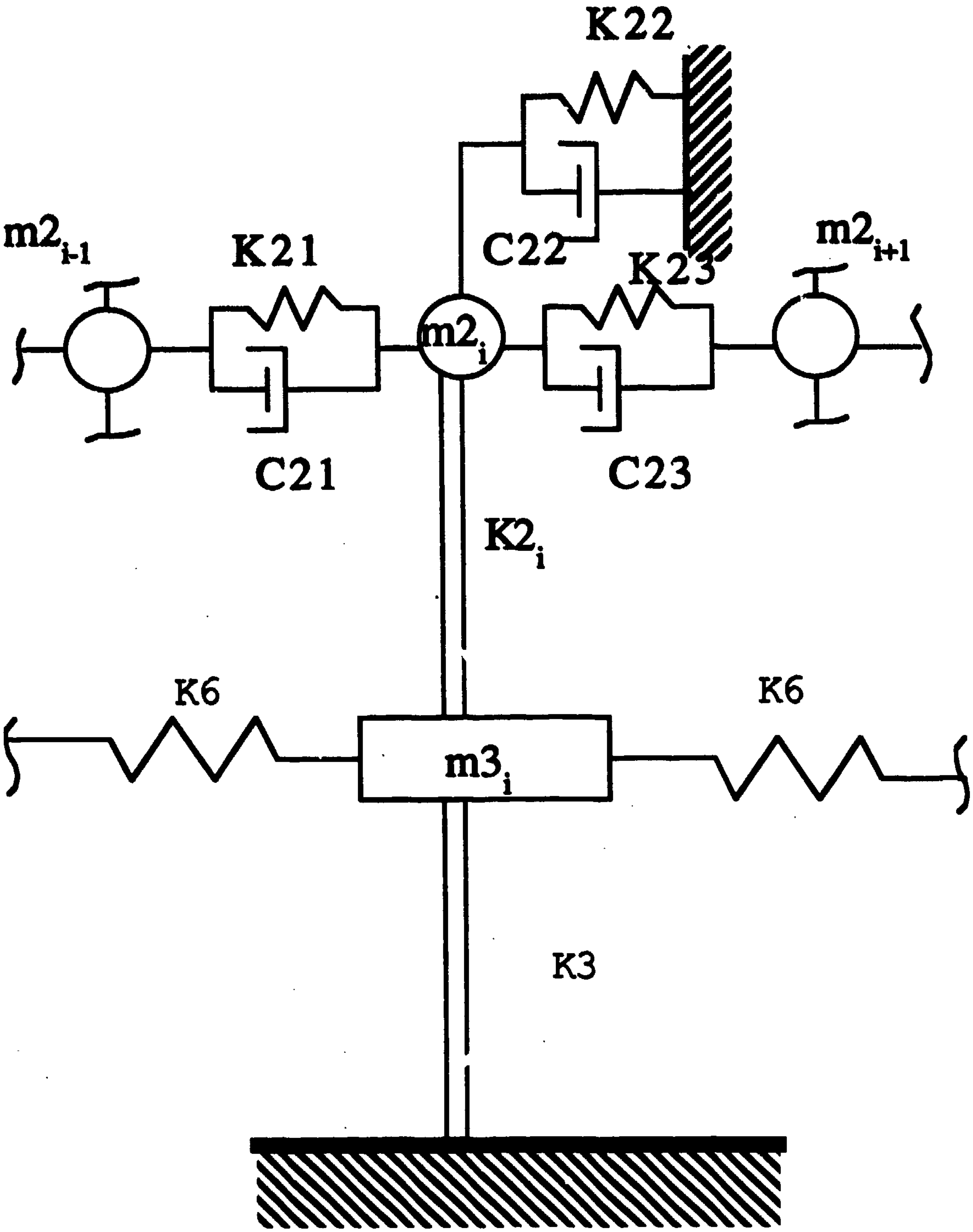


FIG. 5. LUMPED PARAMETER SYSTEM

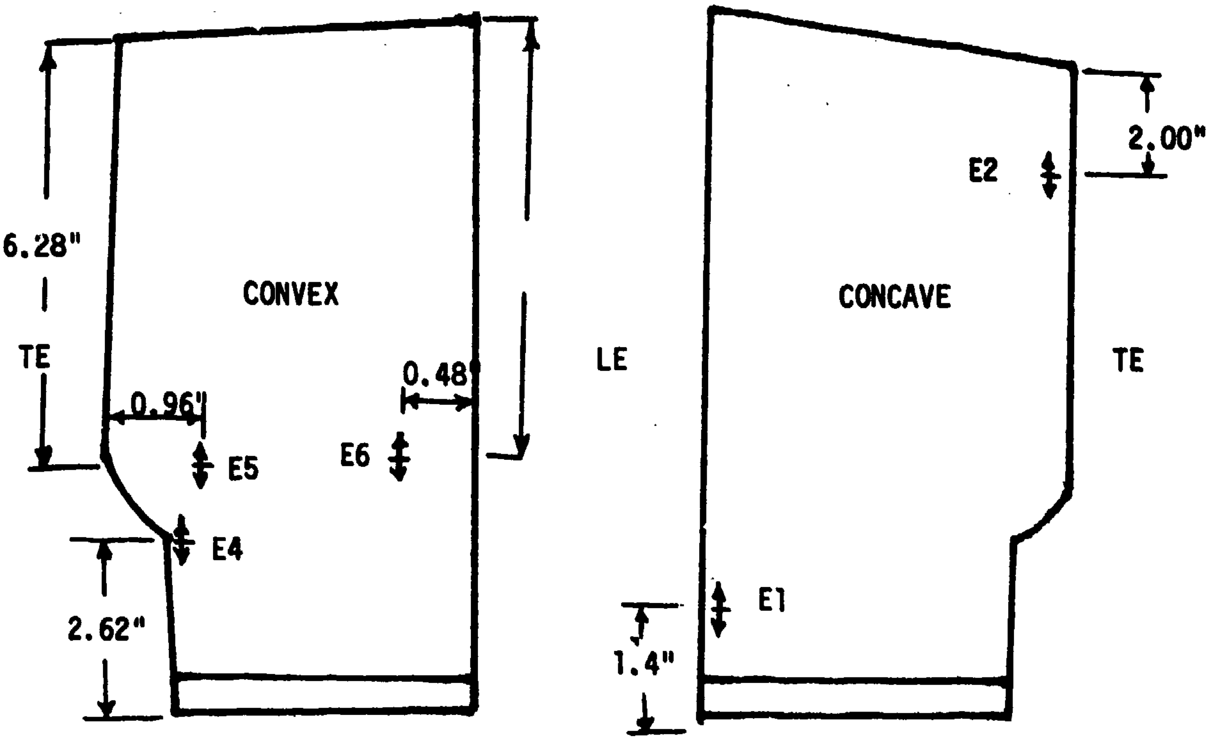


FIG. 6. STRAIN GAGE LOCATIONS

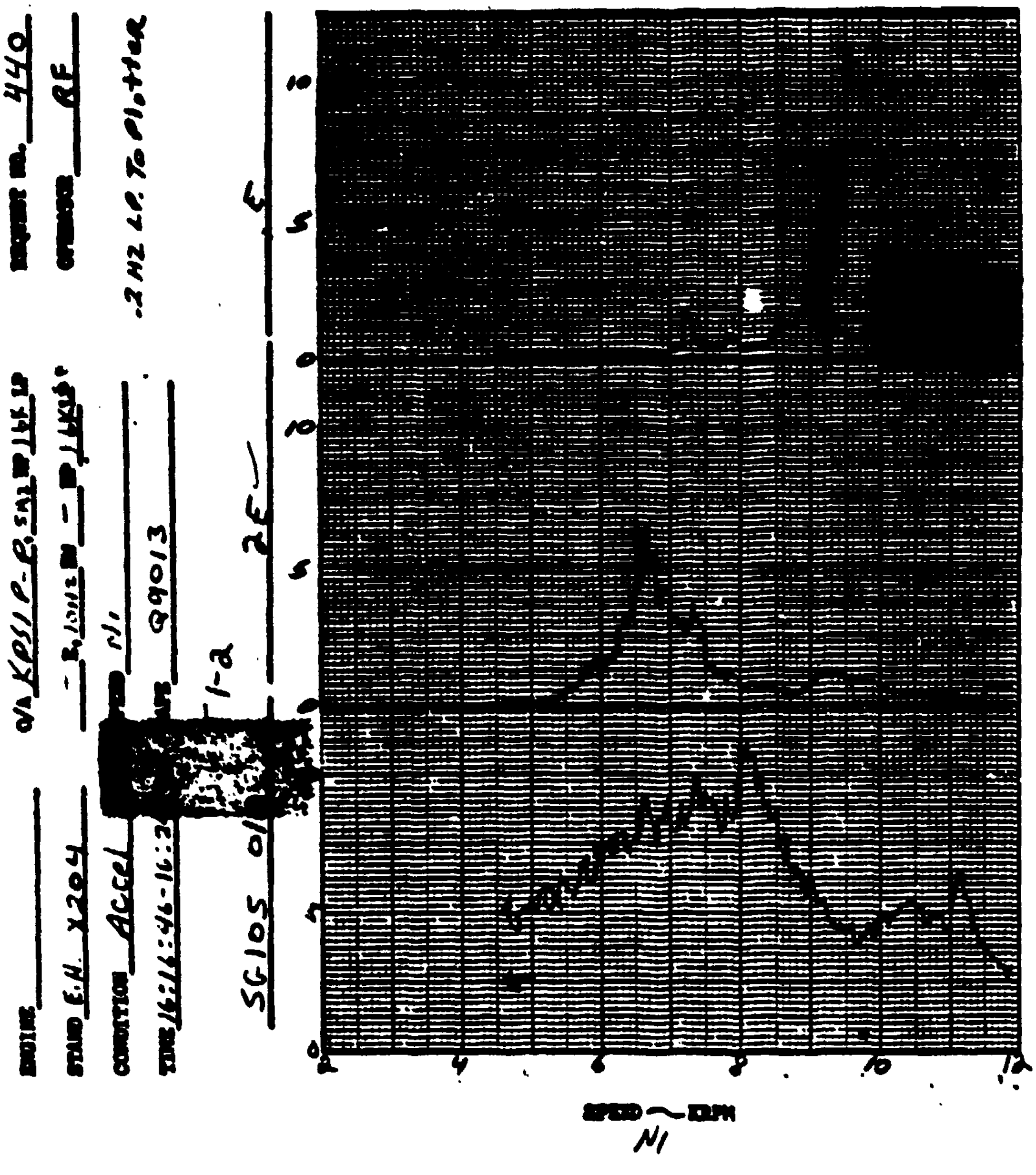


FIG. 7. REPRESENTATIVE STRAIN GAGE DATA

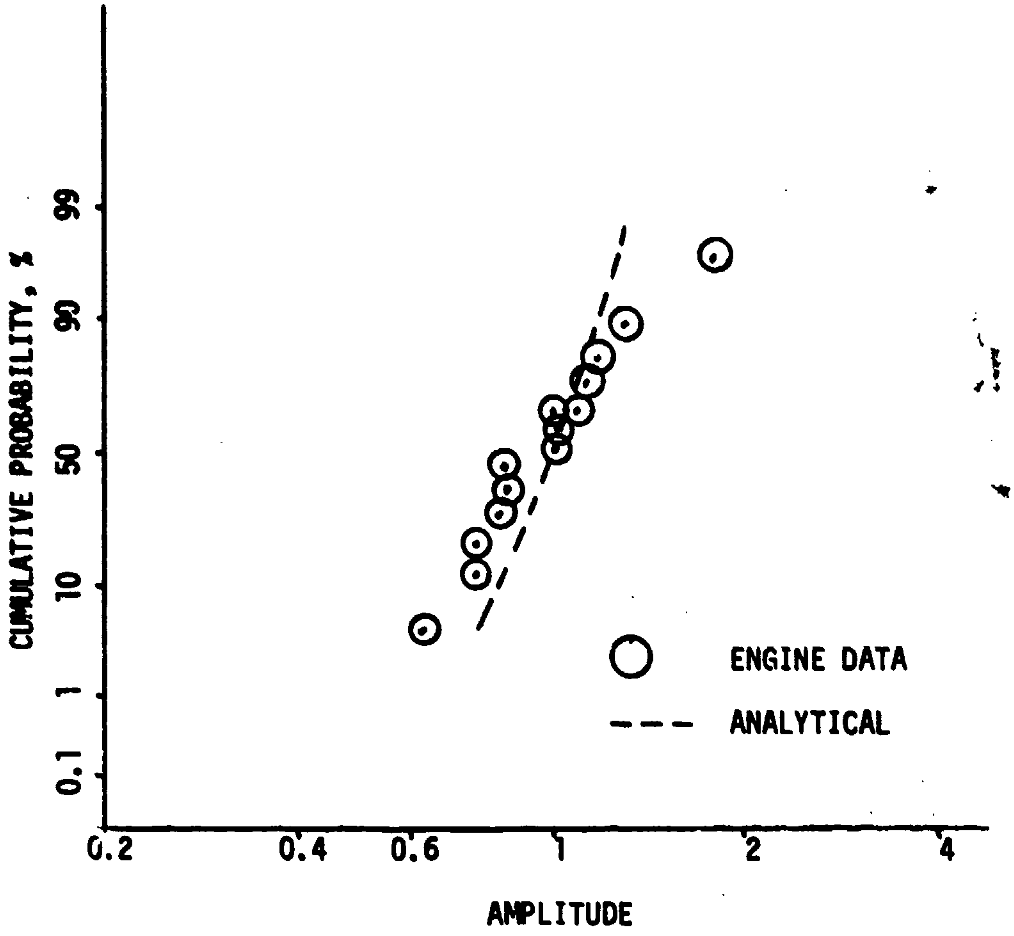


FIG. 8. RESULTS USING SIMPLE DAMPING MODEL: 1st BENDING

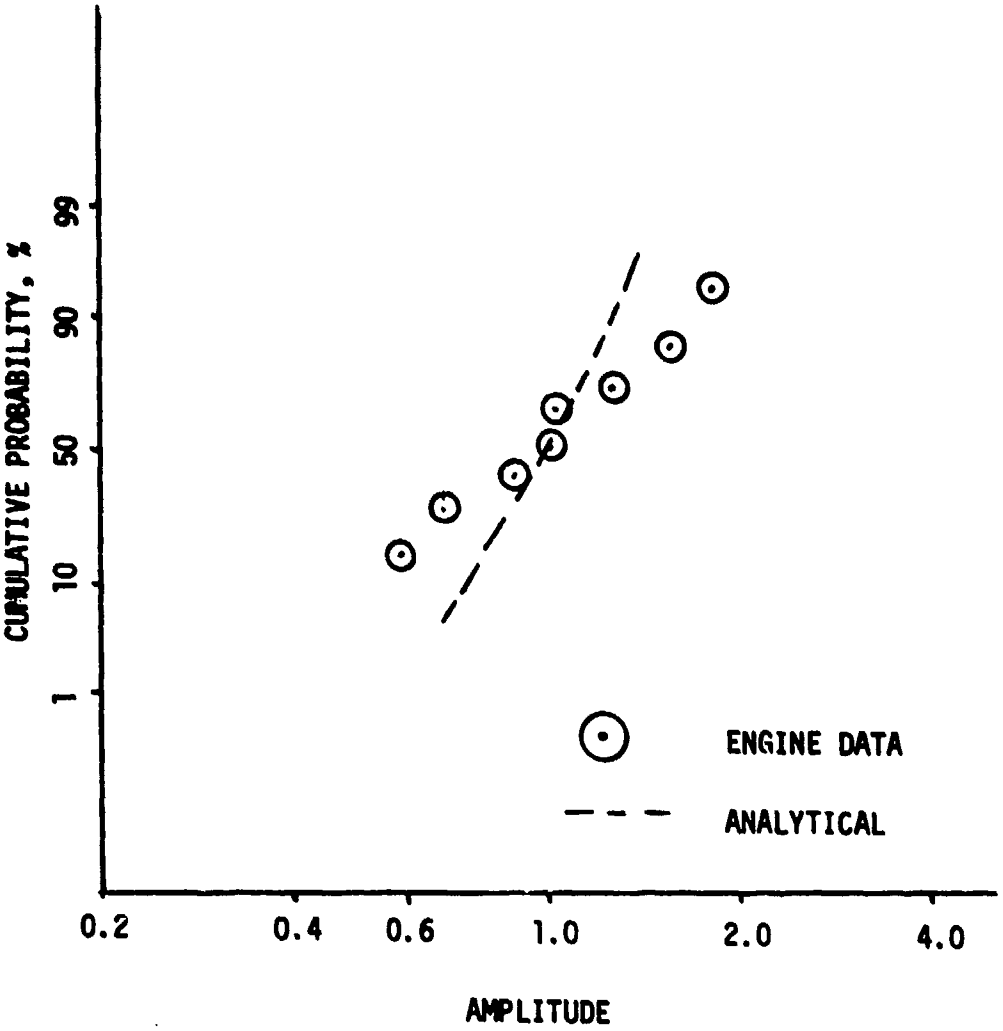


FIG. 9. RESULTS USING SIMPLE DAMPING MODEL: 2nd BENDING

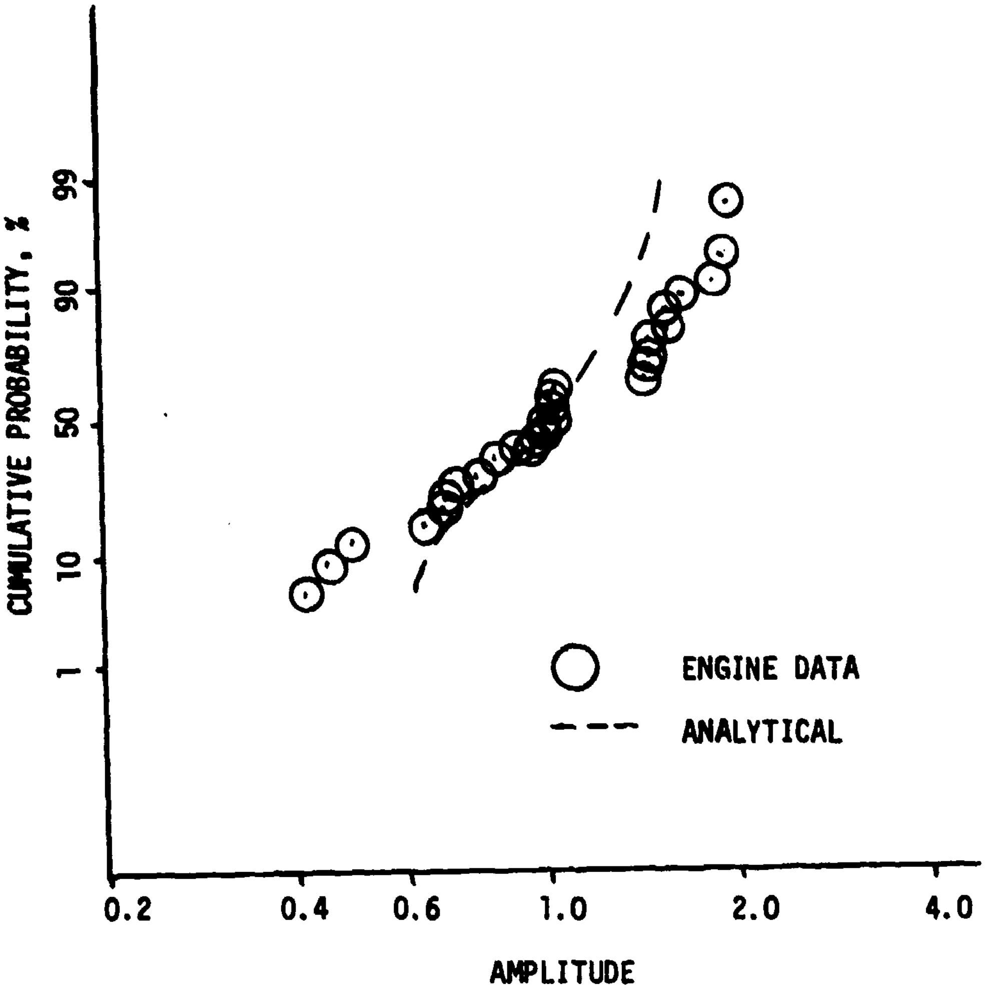


FIG. 10. RESULTS USING SIMPLE DAMPING MODEL: 1st TORSION

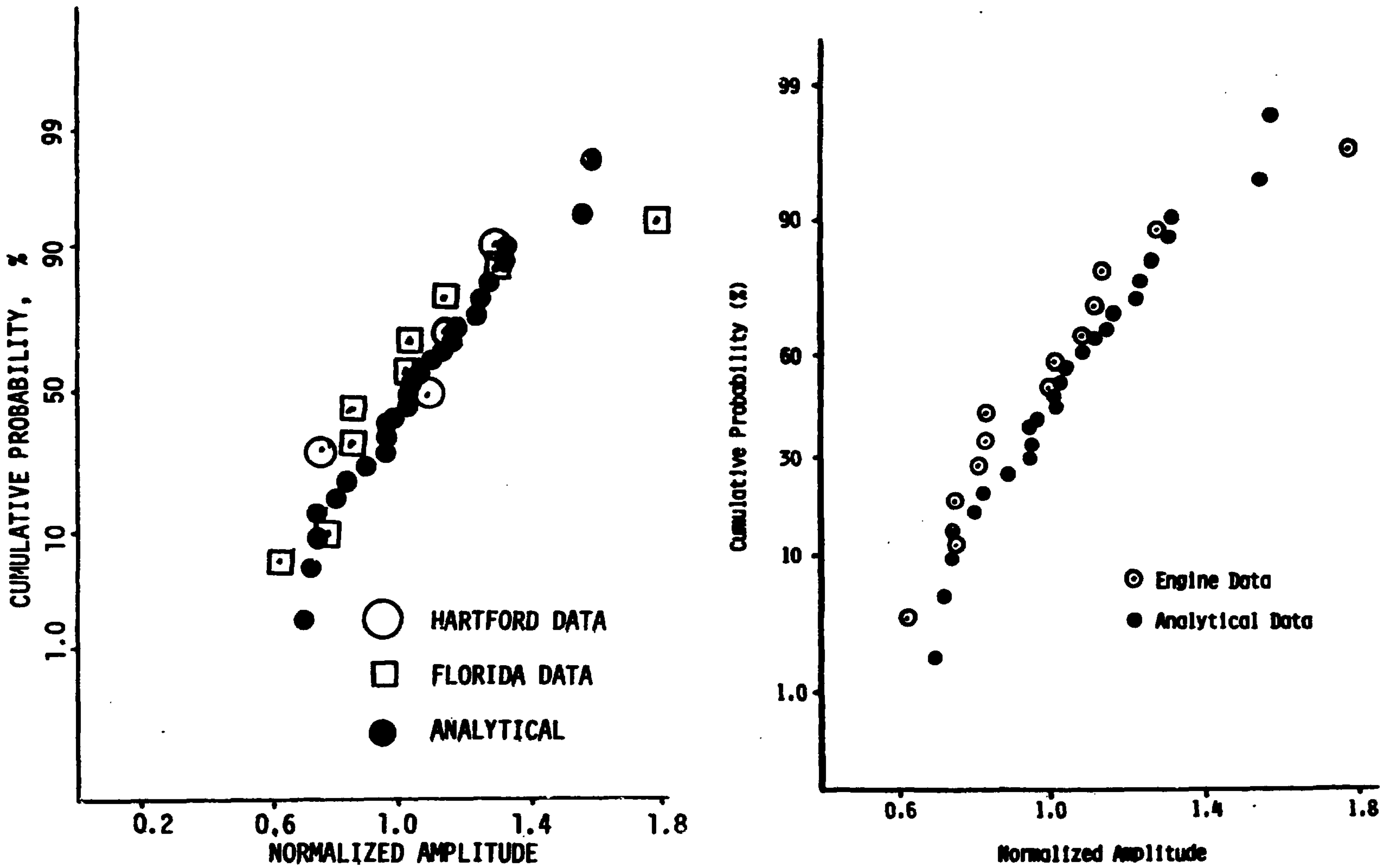


FIG. 11. RESULTS USING AERODYNAMIC CODE: 1st BENDING

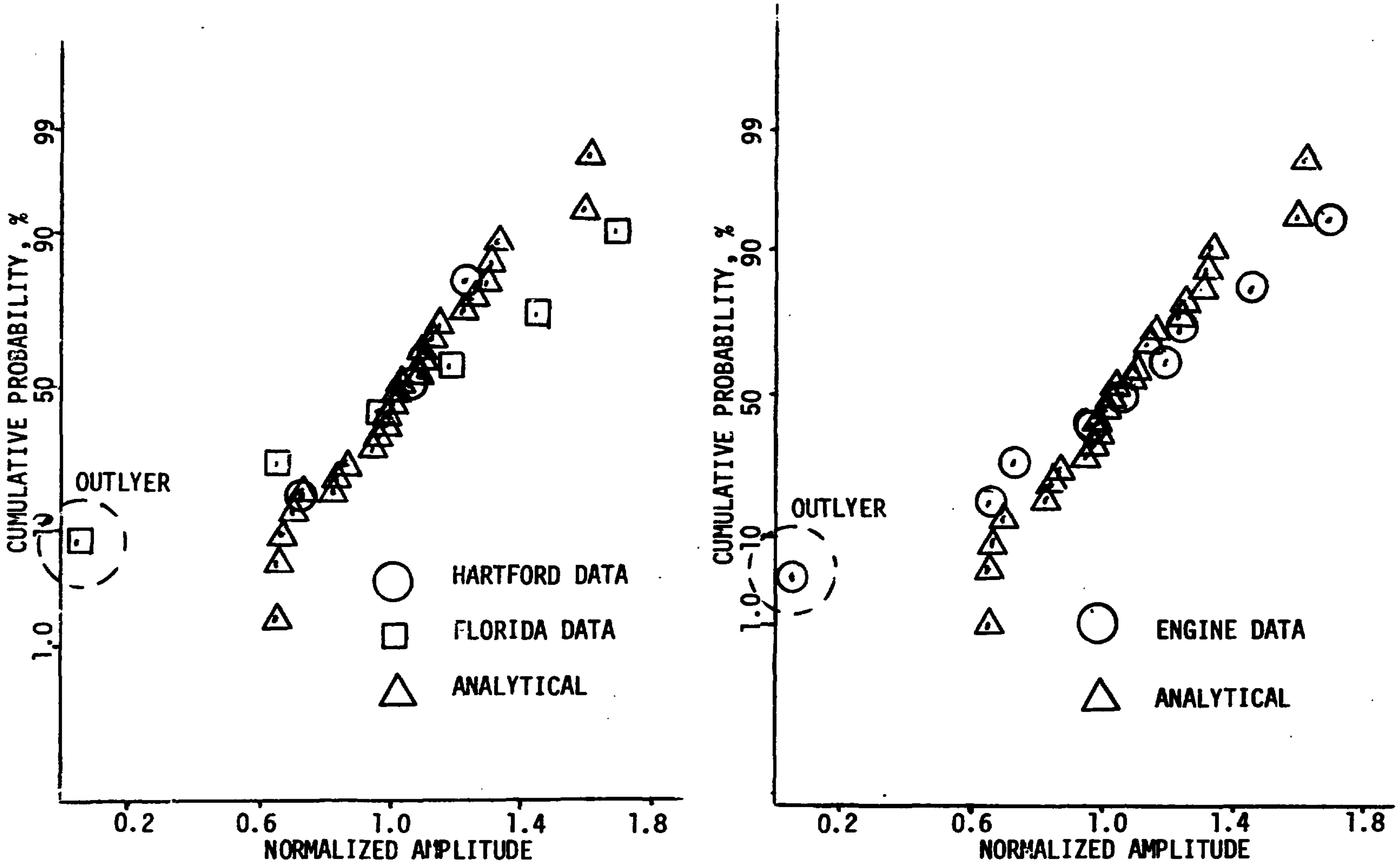


FIG. 12. RESULTS USING AERODYNAMIC CODE: 2nd BENDING WITH OUTLYER

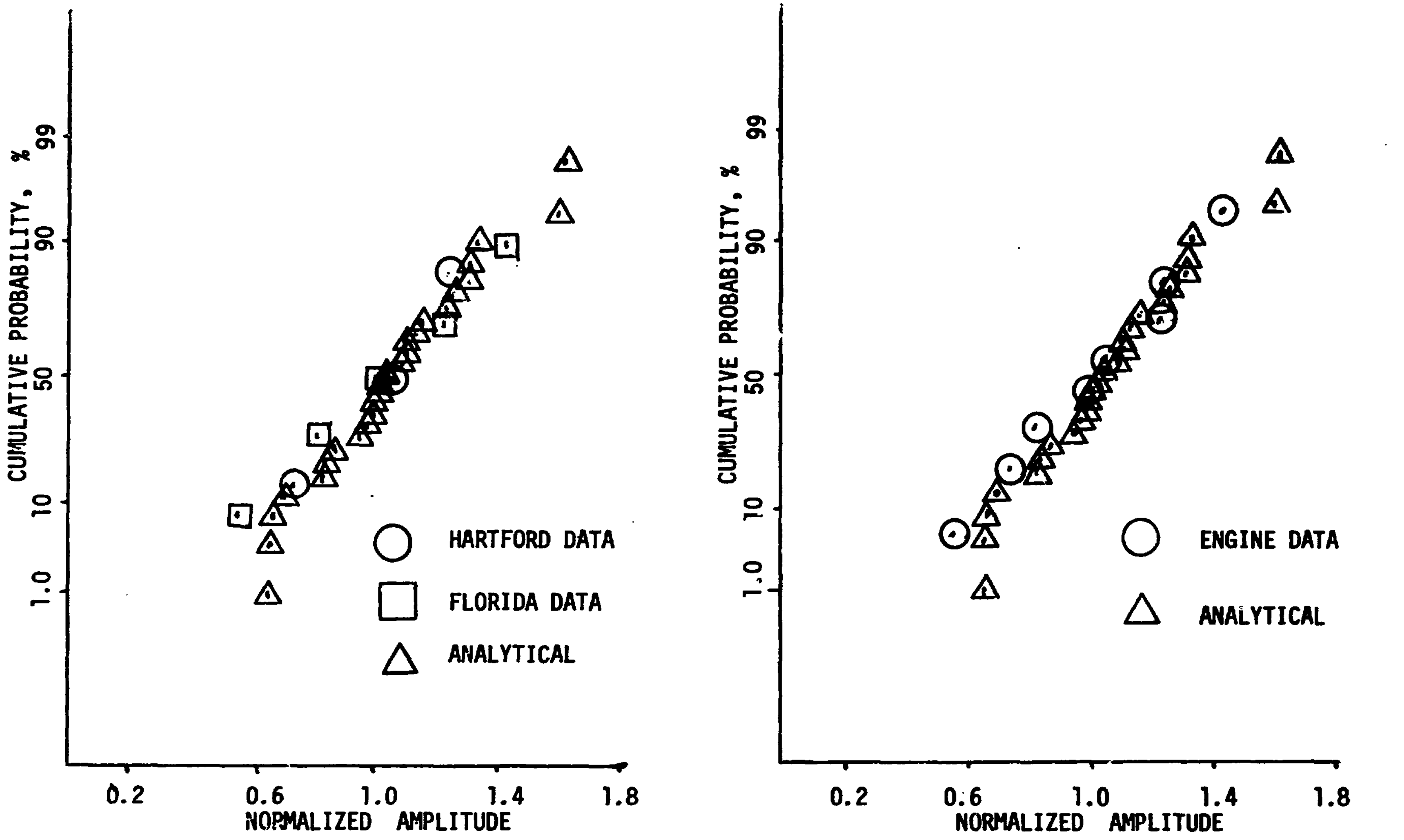


FIG. 13. RESULTS USING AERODYNAMIC CODE: 2nd BENDING WITHOUT OUTLYER

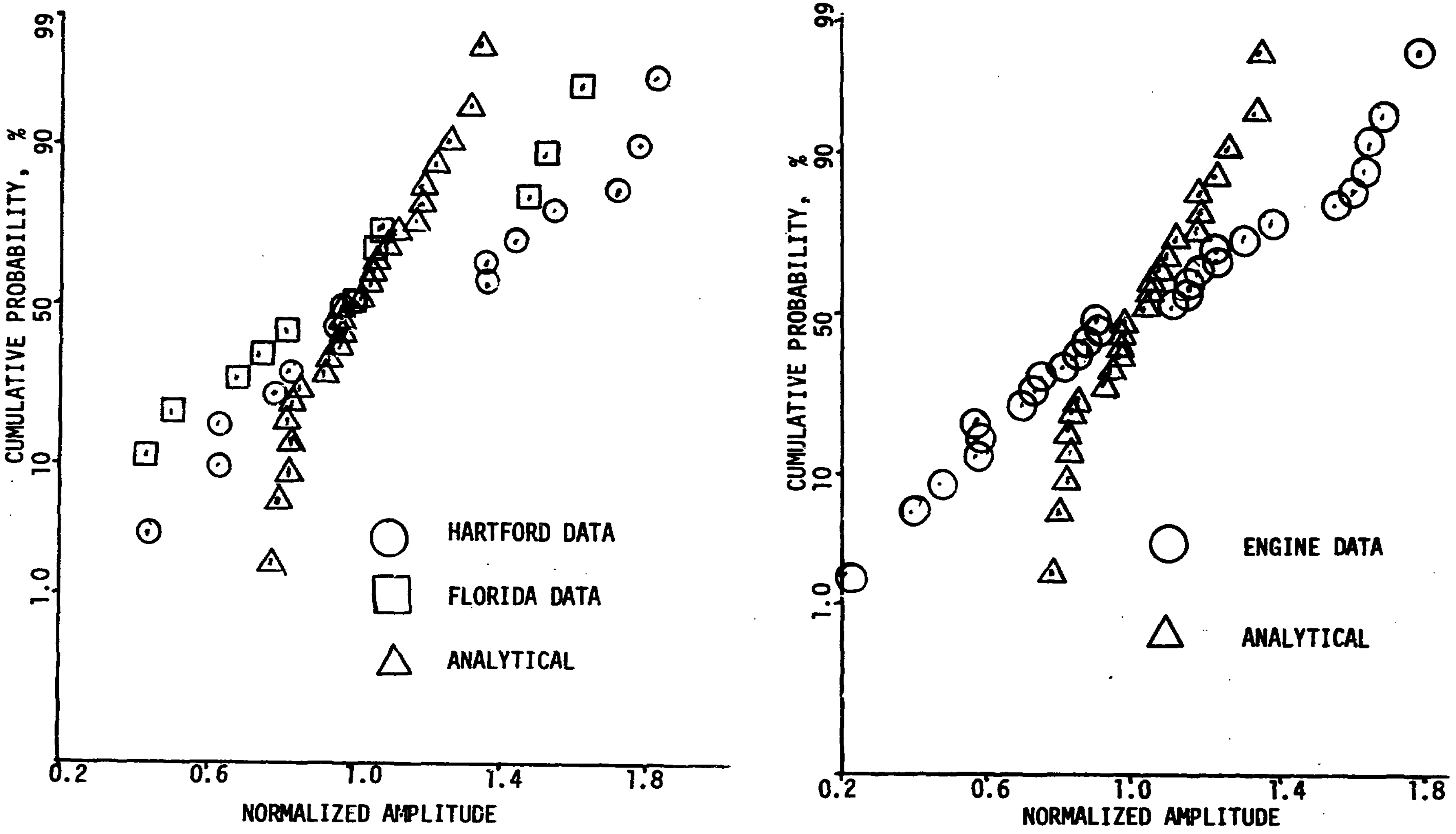


FIG. 14. RESULTS USING AERODYNAMIC CODE: 1st TORSION

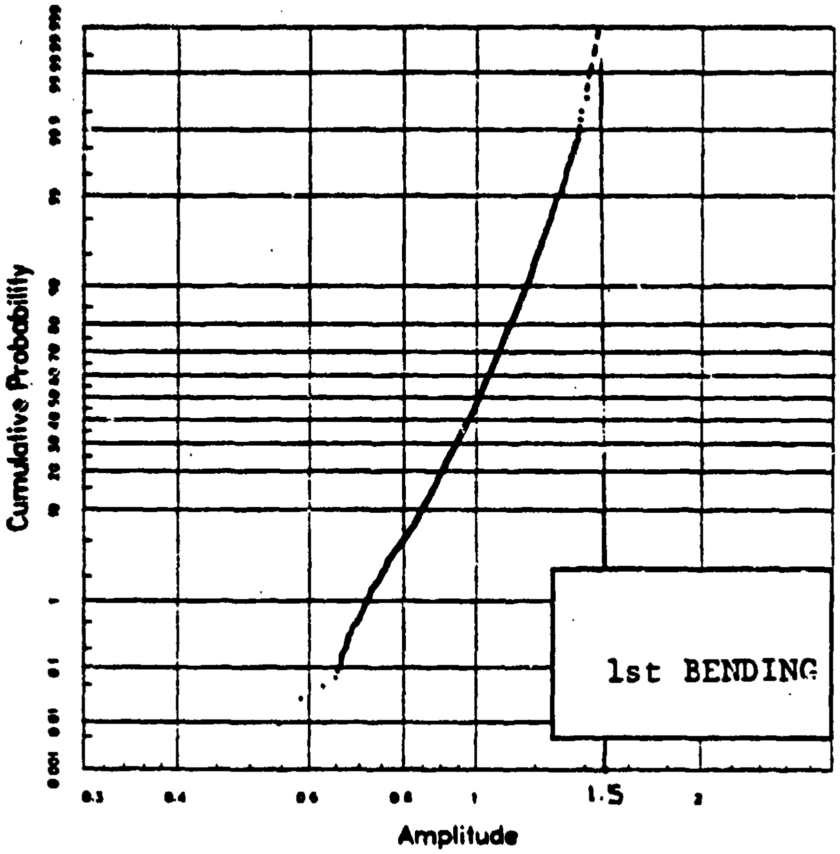


FIG. 15. 200 DISK SIMULATION FOR 1st BENDING

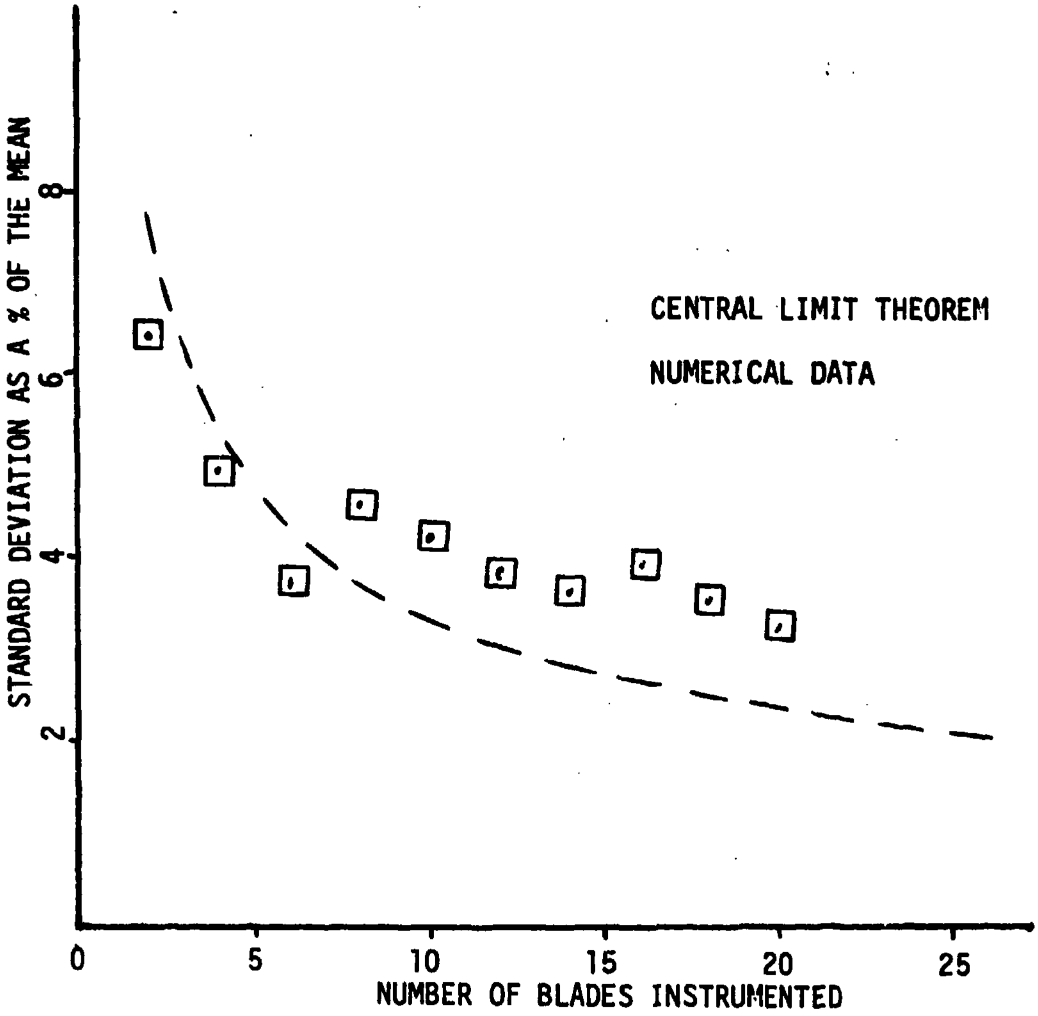


FIG. 16. STANDARD DEVIATION IN THE MEAN AMPLITUDE

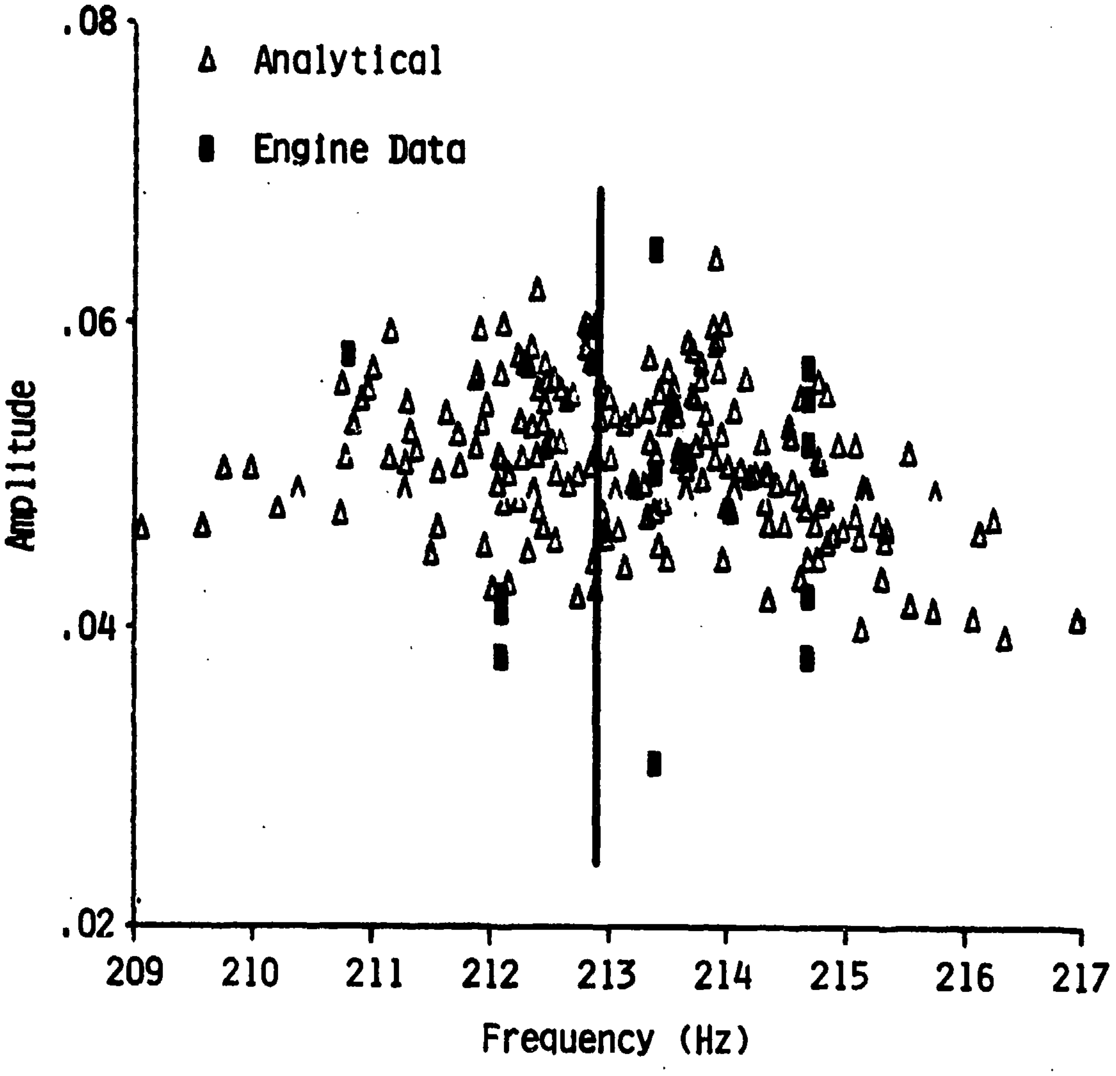


FIG. 17. AMPLITUDE VS. BLADE ALONE FREQUENCY, 1st BENDING

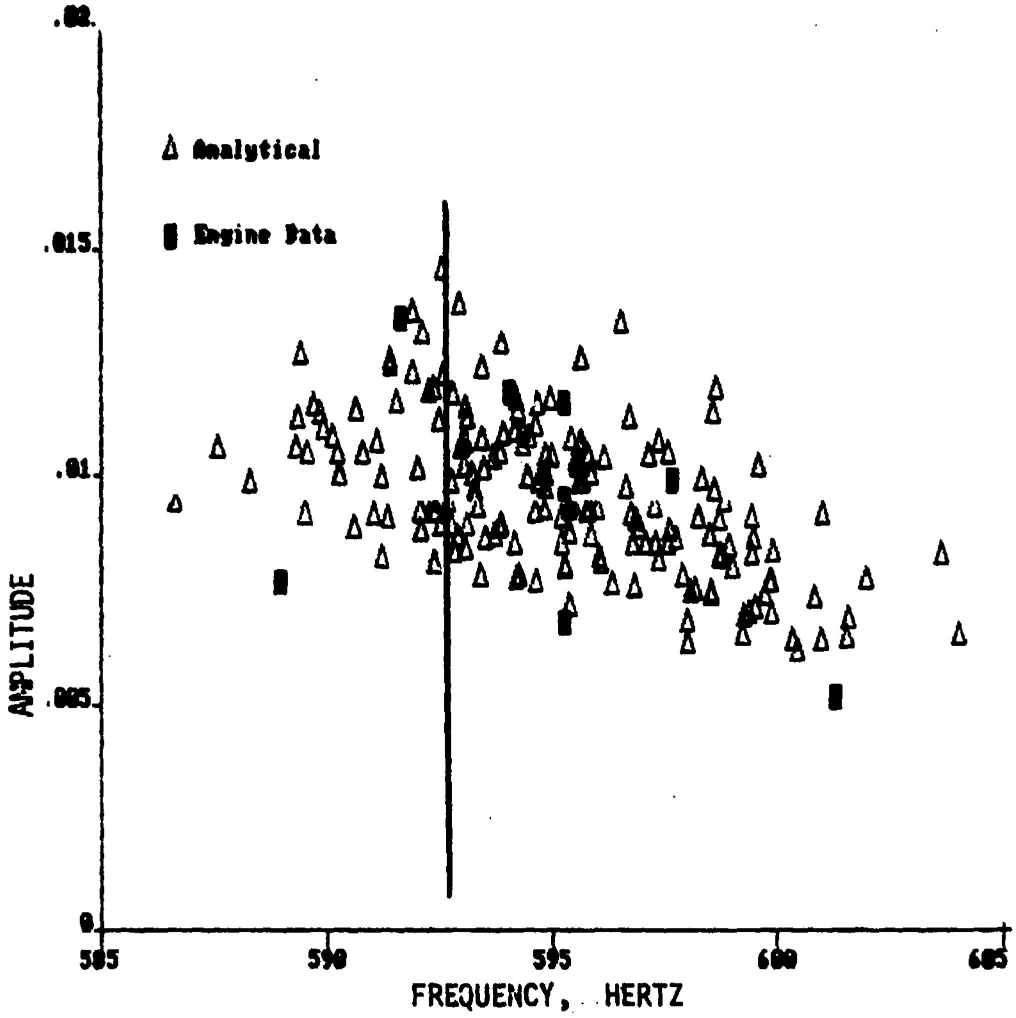


FIG. 18. AMPLITUDE VS. BLADE ALONE FREQUENCY: 2nd BENDING

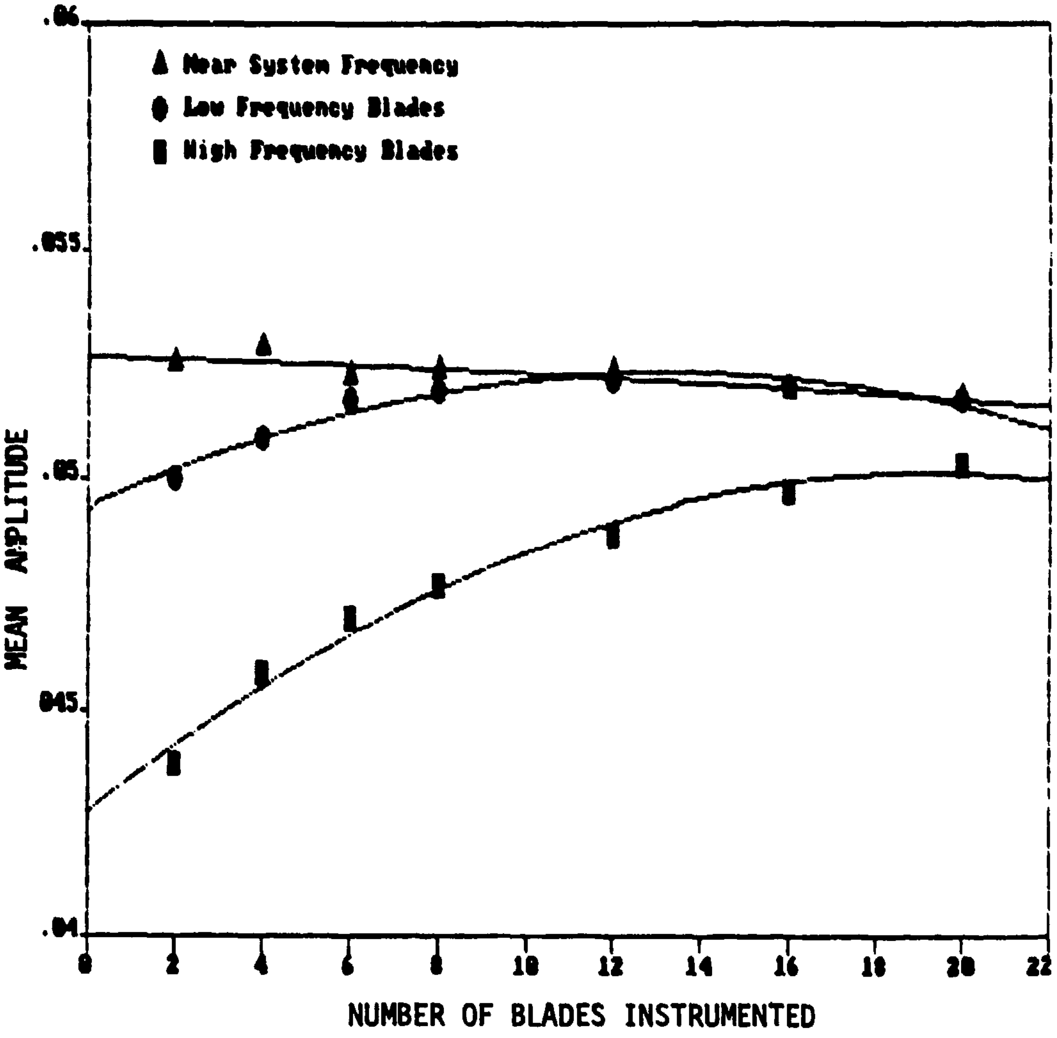


FIG. 19. MEAN AMPLITUDE AS A FUNCTION OF N

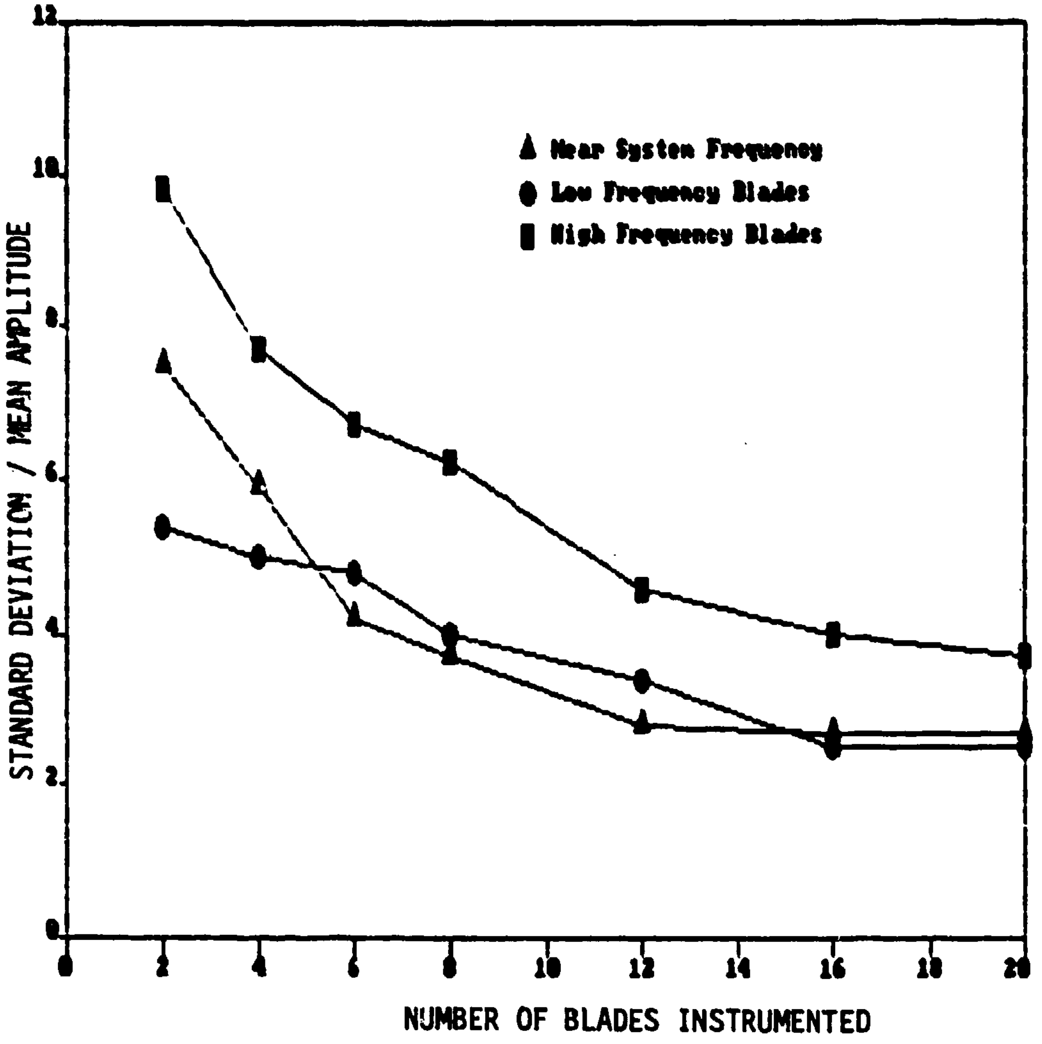


FIG. 20. STANDARD DEVIATION IN MEAN AMPLITUDE

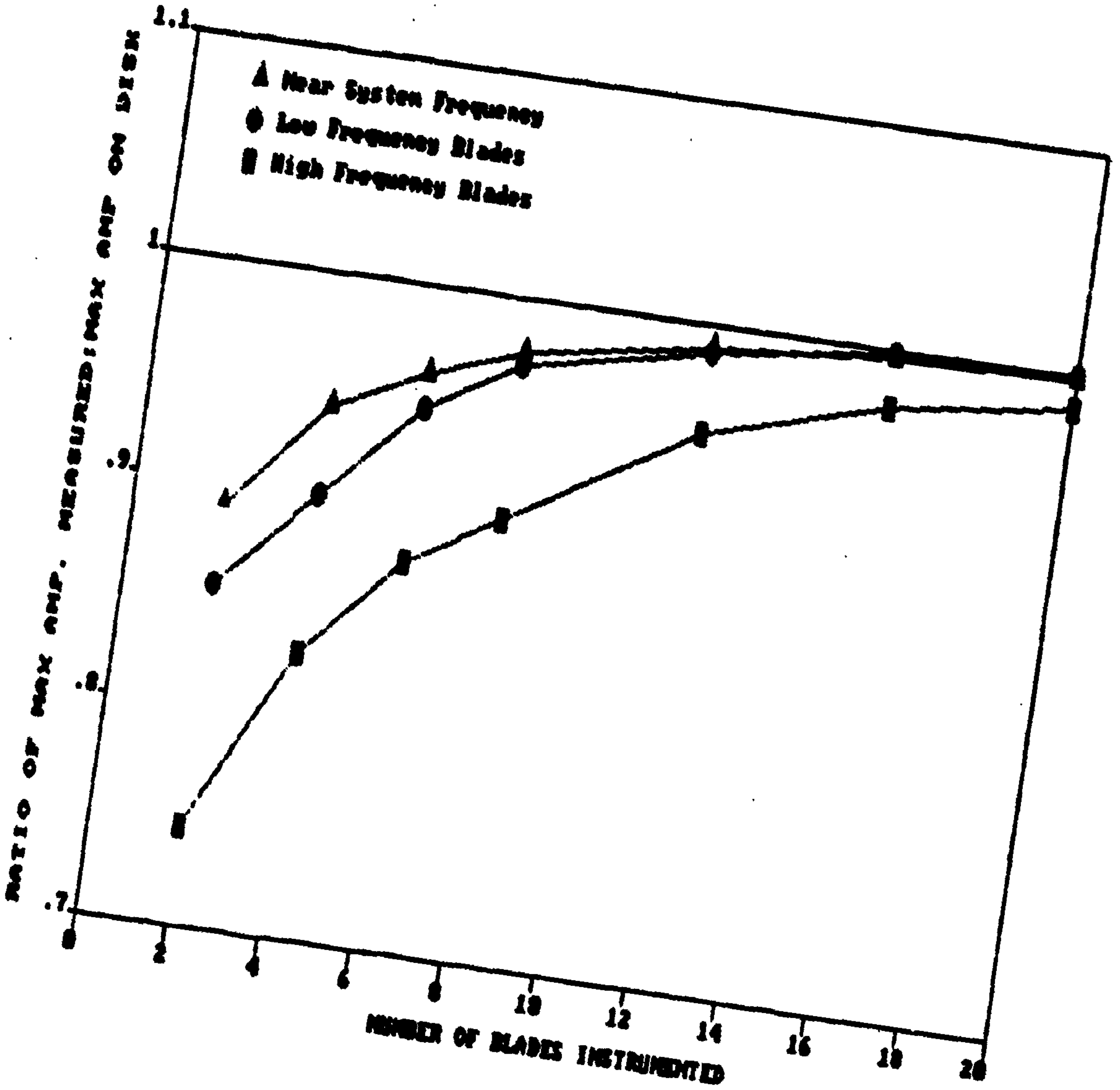


FIG. 21. MAX AMPLITUDE RATIO, R

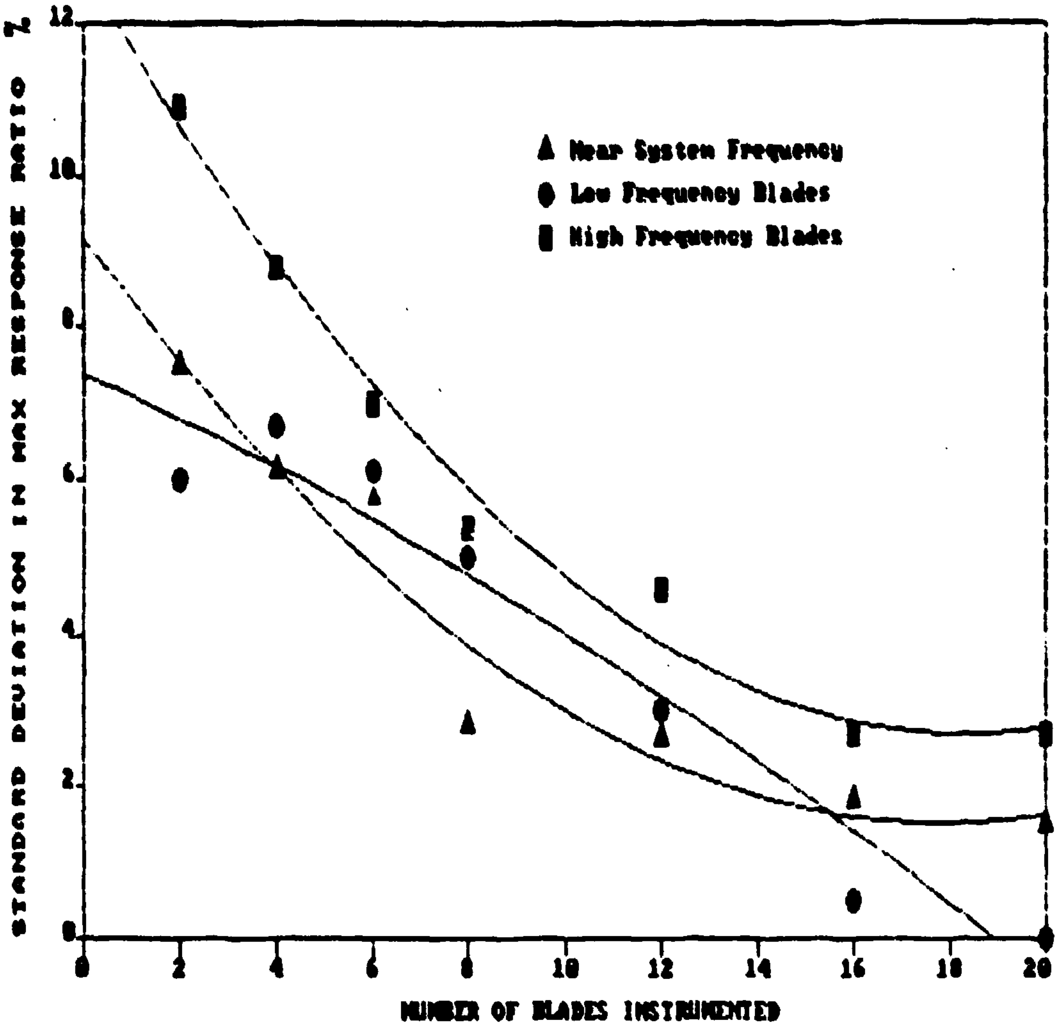


FIG. 22. STANDARD DEVIATION IN R

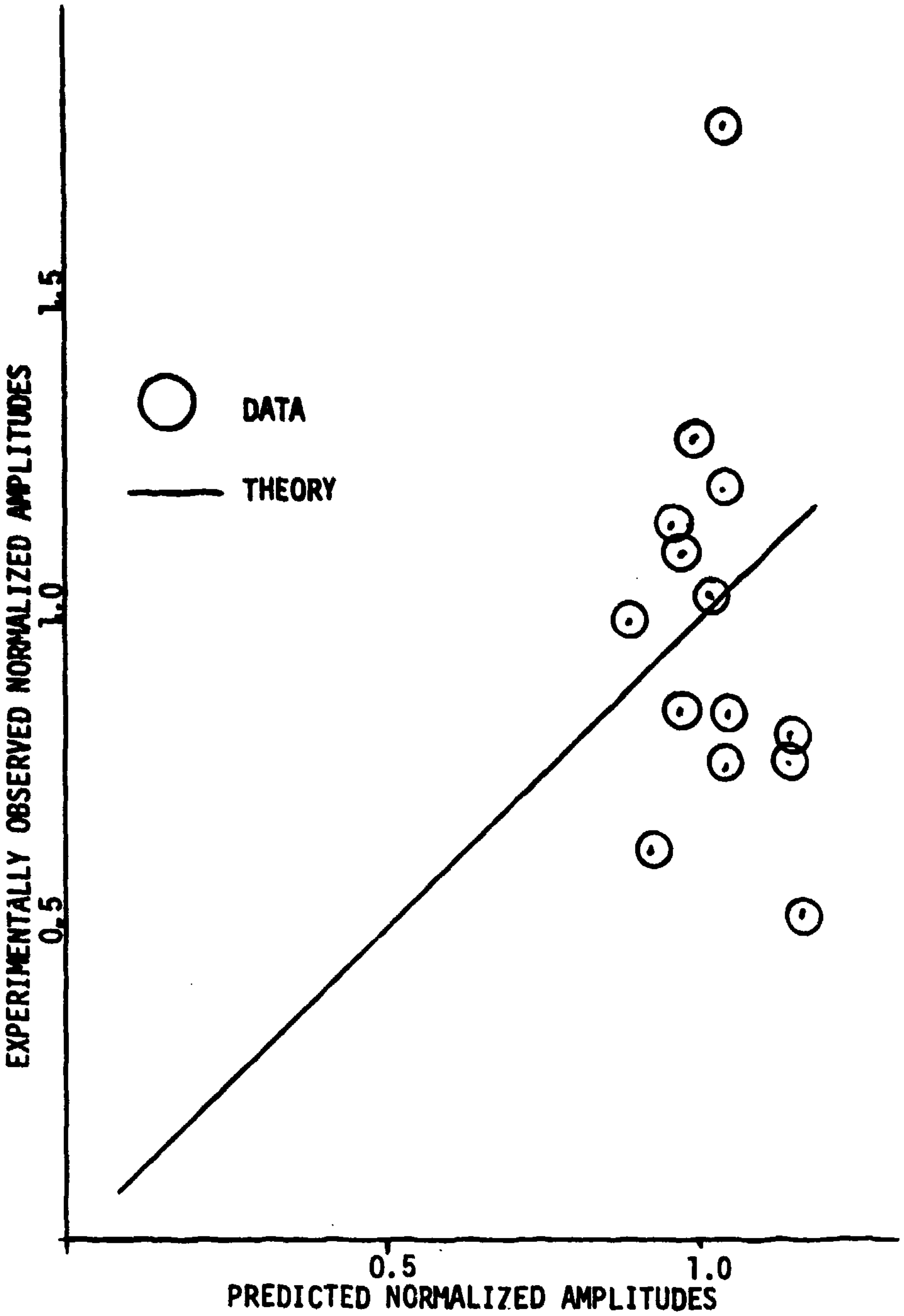


FIG. 23. ANALYSIS OF TEST DISK

REFERENCES

1. Hoosac, T.M. and Griffin, J.H., "Model Development and Statistical Investigation of Turbine Blade Mistuning," ASME Journal of Vibration, Acoustics, Stress, and Reliability in Design, Vol. 106, April 1984.

2. Rao, B.M. and Jones, W.P., "Unsteady Airloads for a Cascade of Staggered Blades in Subsonic Flow," 46th Propulsion Energetics Review Meeting, Monterey, California, September 1975.

3. Basu, P. and Griffin, J.H., "The Effect of Limiting Aerodynamic and Structural Coupling in Models of Mistuned Bladed Disk Vibration", in Vibrations of Blades and Bladed Disk Assemblies, ed. by R.E. Kielb and N.F. Rieger, American Society of Mechanical Engineers, 1985.

4. Miller, Irwin and Freund, John E., Probability and Statistics for Engineers, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1965.

APPENDIX A: TRACKING PLOTS OF ENGINE DATA

FLORIDA DATA

STRESS - KSI (AVG. P/P) vs KRPM

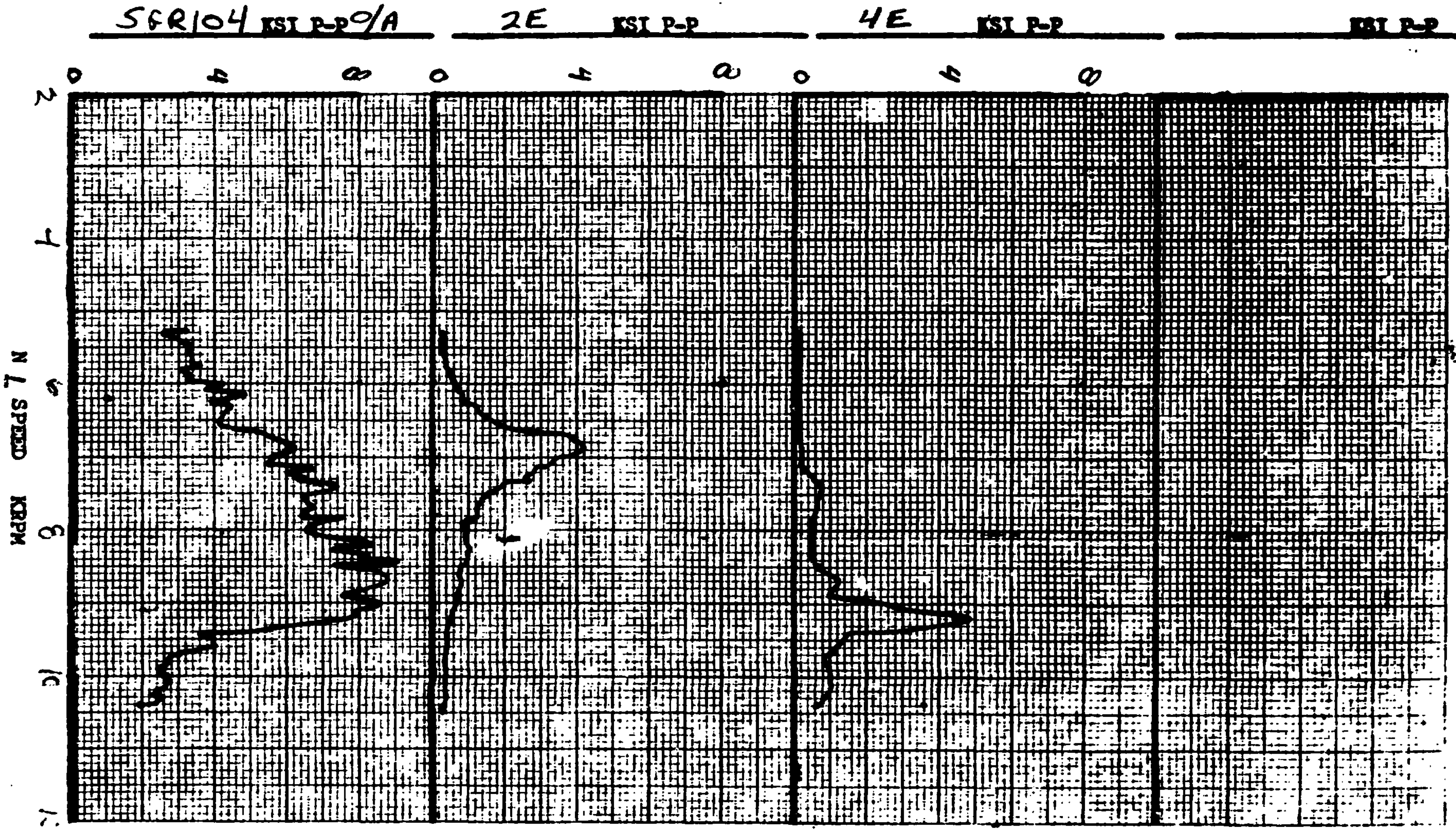
ENGINE P690	O/A KPS1 , — HP 16K LP	REQUEST NO. 831
STAND A-9	2,4 E 10 HZBW — HP 16K LP	OPERATOR RF
CONDITION Accel EV#9	TIME 18:27:25-18:28:25	TAPE AX025064

T1-1

SGR104

①

1-12



1 Hz L.P. Filter on output to plotter

T1-2
SGR/05
①

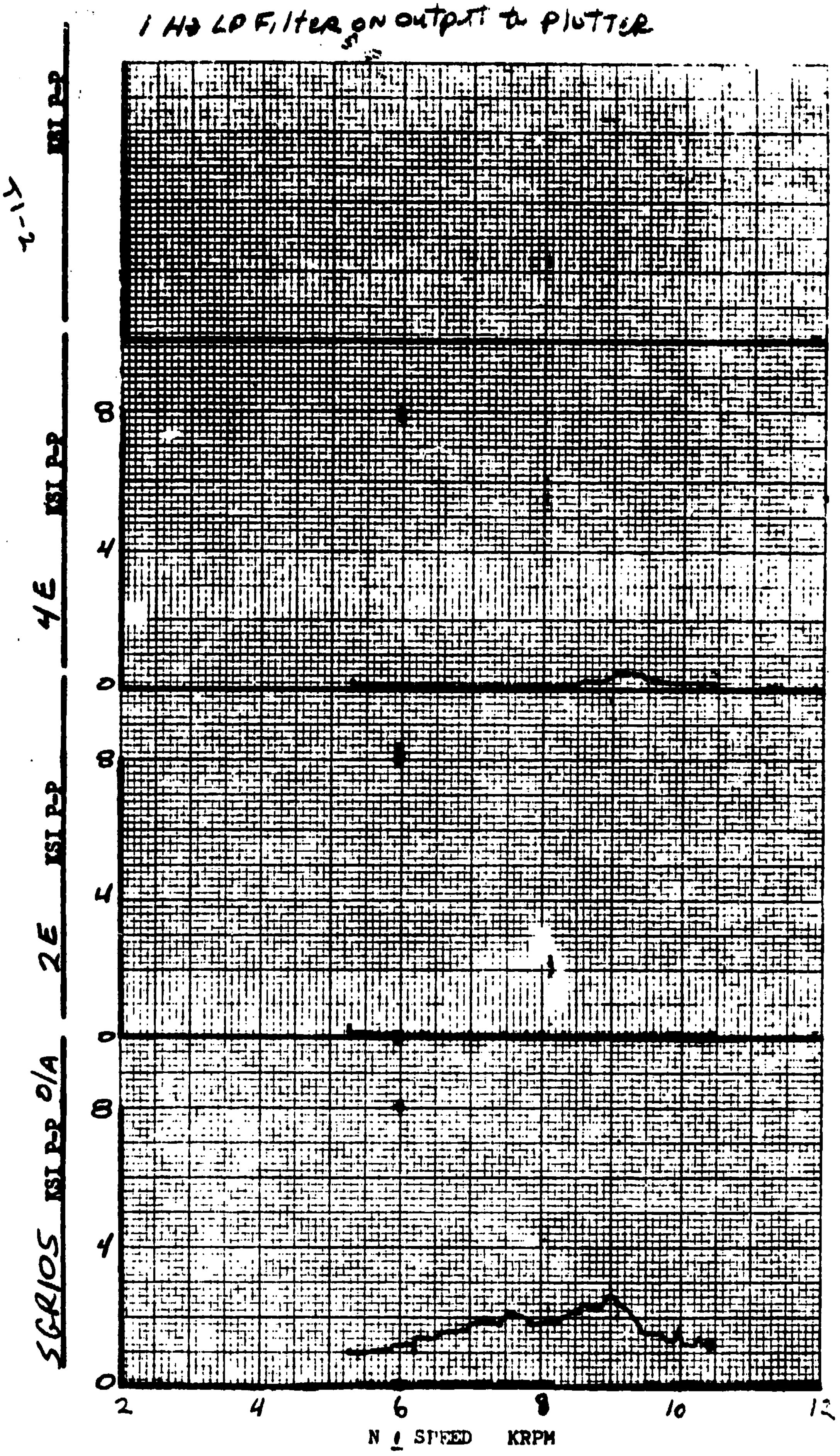
STRESS - KSI (AVG, P/P) vs KRPM

ENGINE P690
STAND A-9
CONDITION Accel EV #9

O/A KPSI — HP/6K LP
2,4 E 10KHz BW — HP/6K LP
TIME 18:27:25-18:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025044

1 Hz LP Filter on output to plotter



T1-4

SGR107

①

STRESS - KSI (AVG. P/P) vs KRPM

ENGINE P690

STAND A-9

CONDITION Accel E1 #9

O/A KPSI — HP/16K LP

2, 4/E 10Hz BW — HP/16K LP

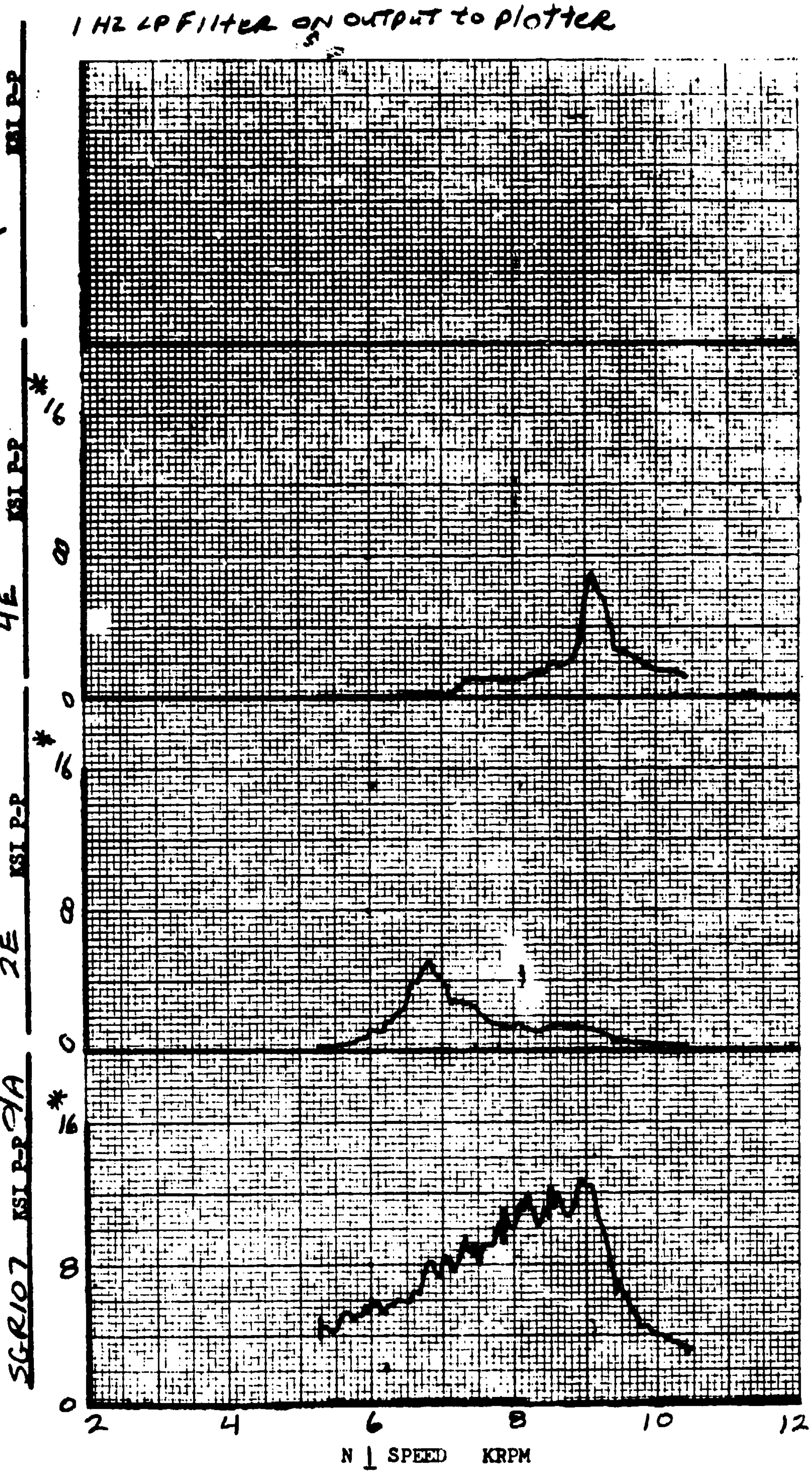
TIME 18:27:25-18:28:25

REQUEST NO. 831

OPERATOR RF

TAPE AX025064

1 Hz LP Filter on output to plotter



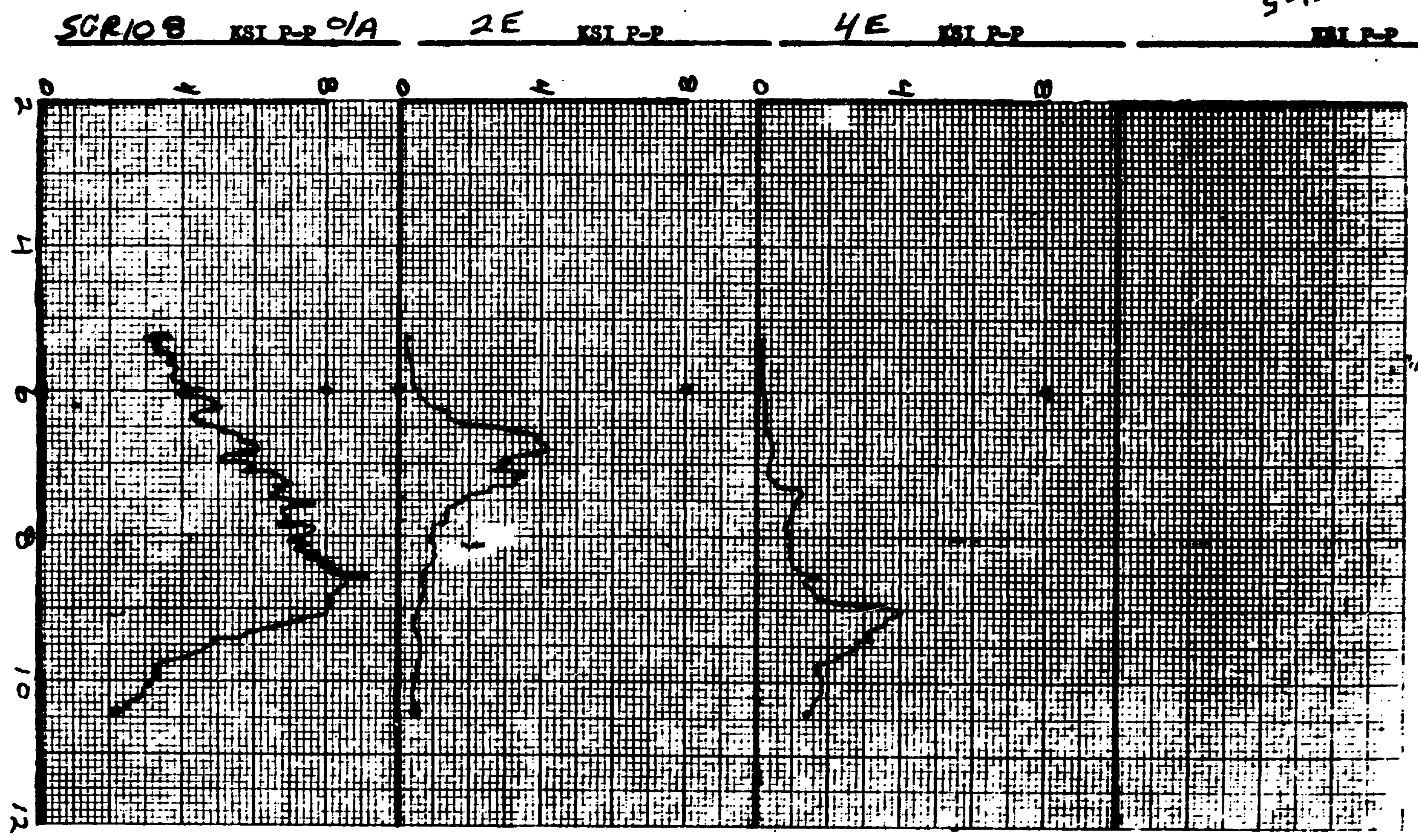
STRESS - KSI (AVG. P/P) vs KRPM

ENGINE P690
STAND A-9
CONDITION Accel Ev #9

O/A KPSI — HP 16K LP
2.4 E, 10% BW — HP 16K LP
TIME 18:27:55 - 18:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025064

T1-5
SGR108
①



1 Hz LP Filter on output to plotter

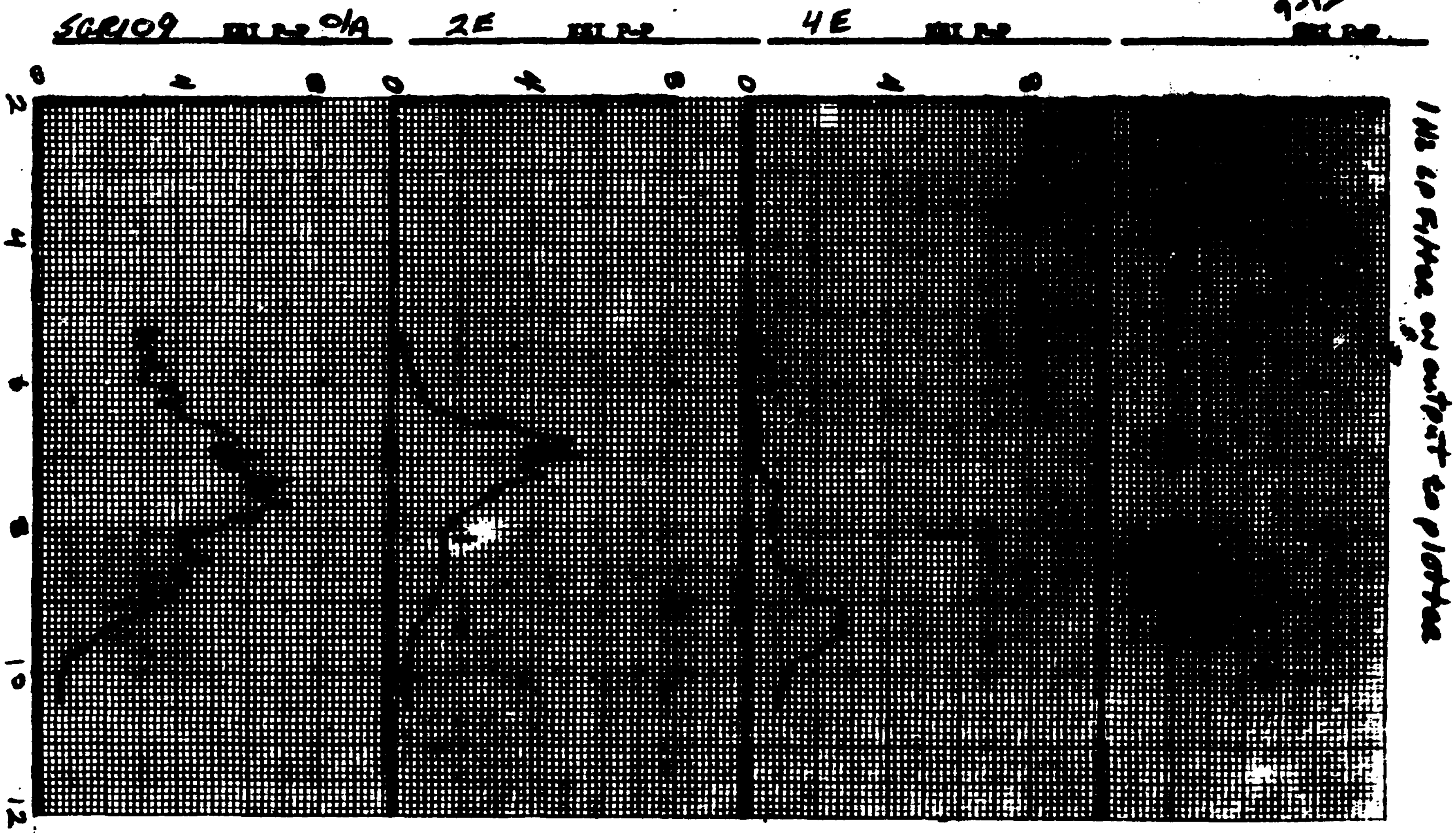
[illegible] - [illegible] ([illegible] P/P) vs KRPM

T1-6
SGR109
①

ENGINE P690
STAND A-9
CONDITION Accel EV#9

O/A KPS1 — HZ 16K LP
2, 4E, 10 HZ BW — HZ 16K LP
TIME 18:27:25-18:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025064



1 Hz LP Filter on output to plotter

STRESS - KSI (AVG., P/P) vs KRPM

ENGINE D690 O/A KPSI — HP 16K LP

STAND A-9 2,4 E 10Hz BW — HP 16K LP

CONDITION Accel EV#9 TIME 18:27:25-18:28:25

REQUEST NO. B31

OPERATOR RF

TAPE AX025064

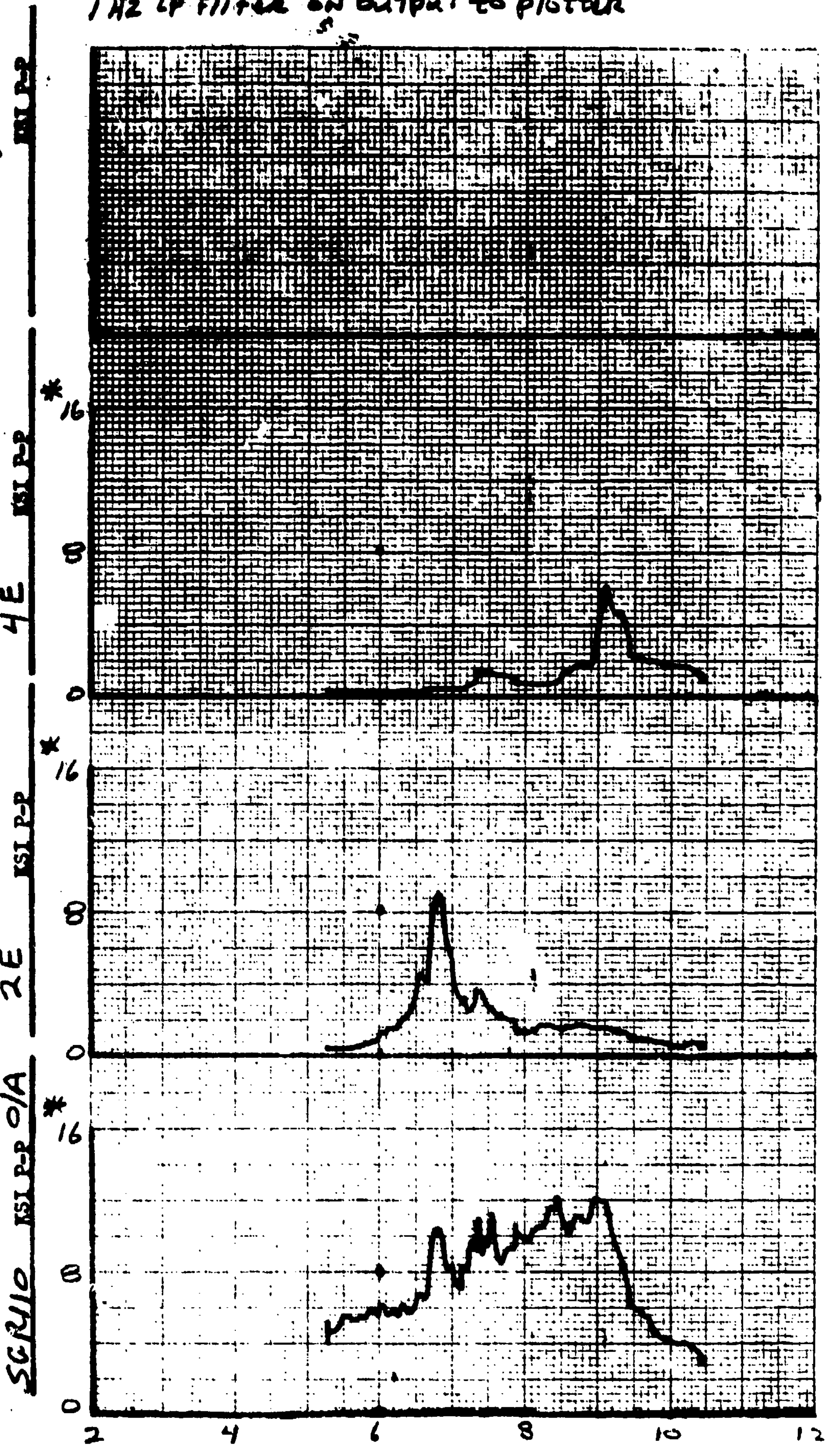
TI-7

SGR110

①

L-1Y

1 Hz LP Filter on output to plotter



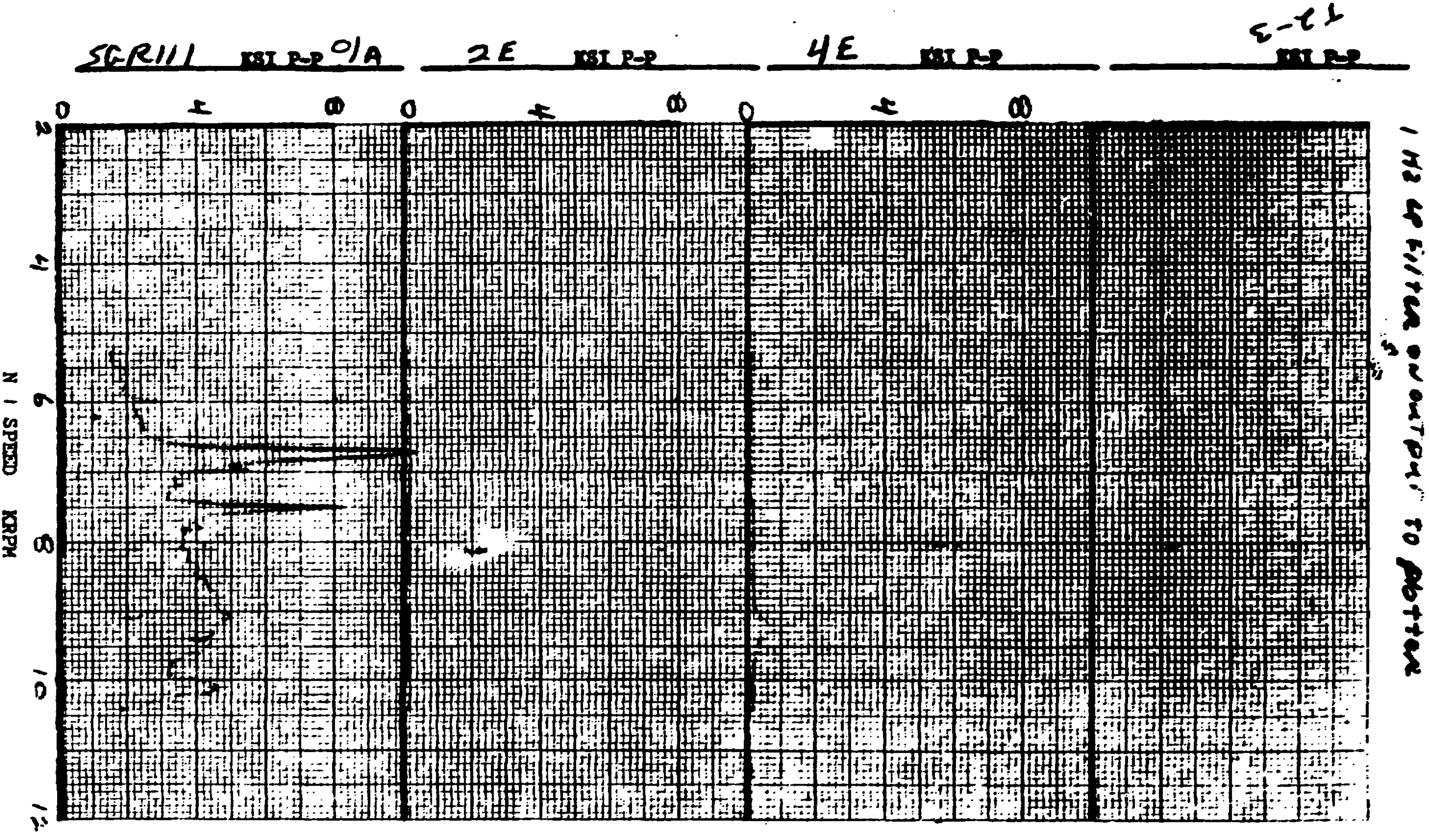
STRESS - KSI (AVG. P/P) vs KRPM

ENGINE P690
STAND A-9
CONDITION Accel EV #7

O/A KPSI, — HP/6K LP
2,4E10 KBW — HP/6K LP
TIME 18:27:25 - 19:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025064

T2-3
SGR111
②



1 Hz LP filter on output to plotter

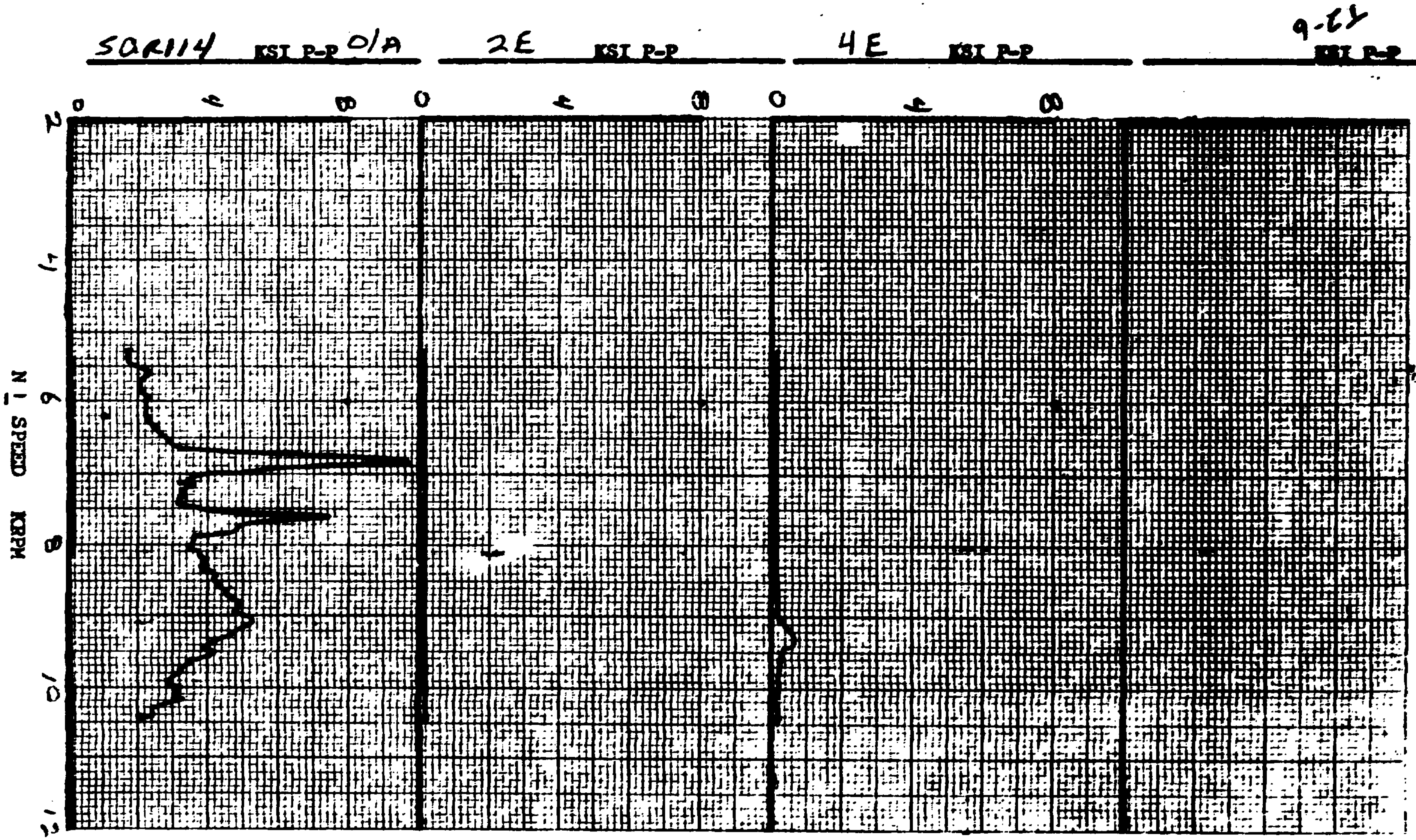
STRESS - KSI (AVG. P/P) vs KRPM

ENGINE P690
STAND A-9
CONDITION Accel EV #9

O/A KPS1 , — HP 16K LP
2,4 E 10Hz BW — HP 16K LP
TIME 18:27:25-18:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025064

T2-6
SGR114
②



1 Hz LP Filter on output to plotter

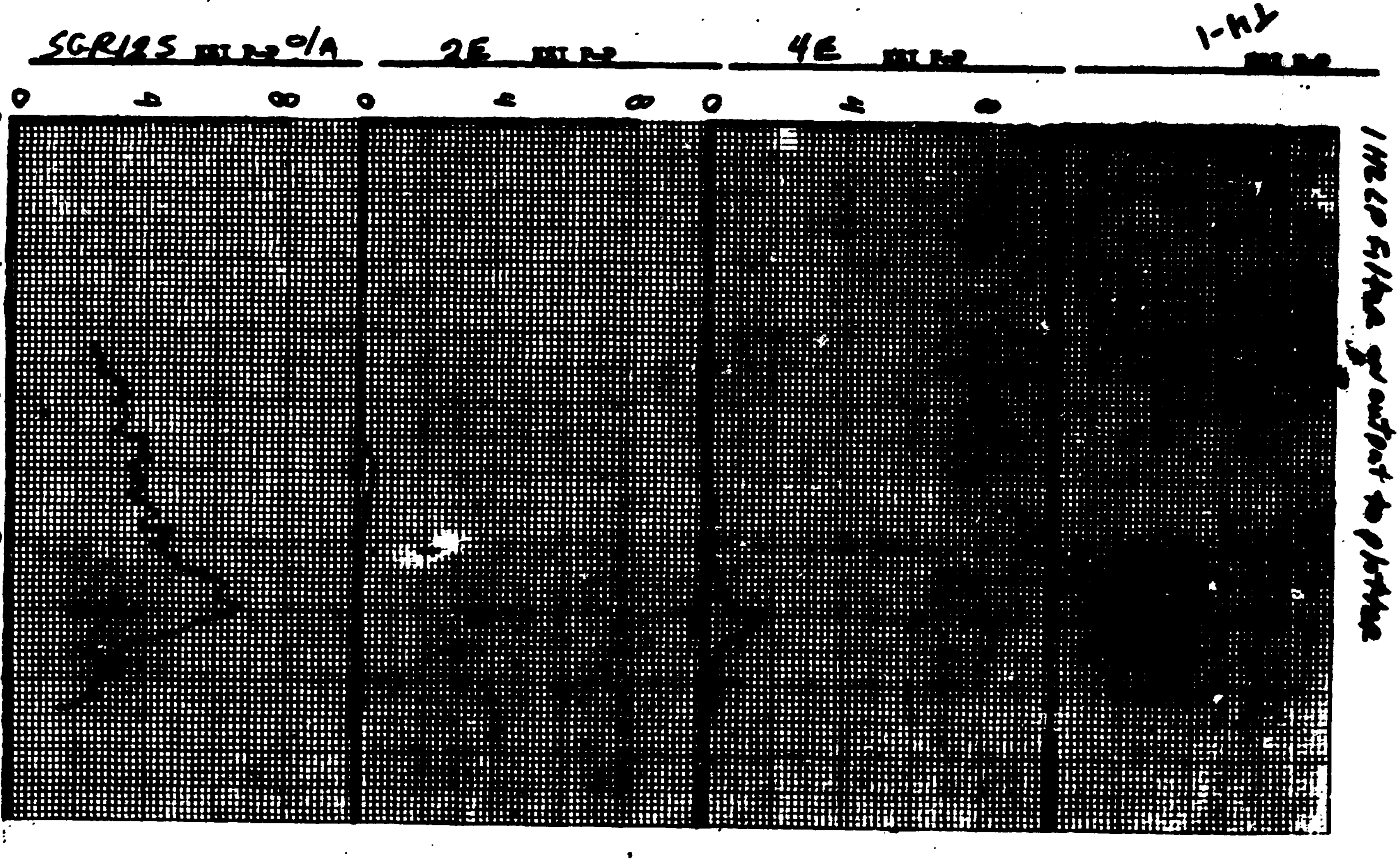
[illegible] - KSI ([illegible] P/P) vs [illegible]

ENGINE P690	O/A KPSI — BP16KLP	REQUEST NO. 831
STAND A-9	24 [illegible] BW — BP16KLP	OPERATOR RF
CONDITION Accel EV #9	TIME 18:27:25-18:28:25	TAPE AX025064

T4-1

SGR125

⑤

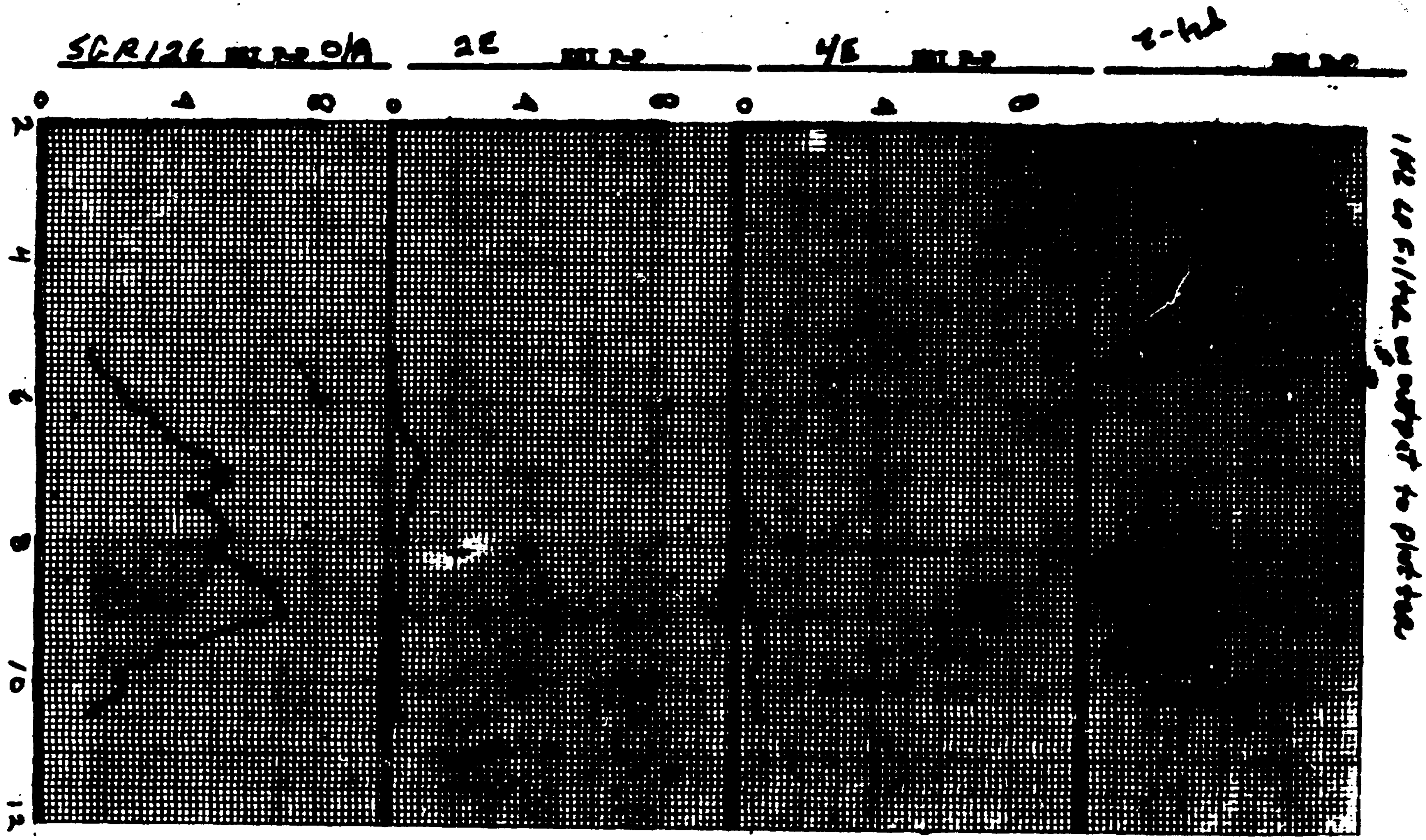


1Hz LP Filter on output to plotter

[illegible] - [illegible] ([illegible] IP/P) vs [illegible]

ENGINE P690
STAND A-9
CONDITION Accel E1 #4
O/A KPS1 — [illegible]KK IP
3-4 [illegible] — [illegible]KK IP
TIME 18:27:25-18:28:25
REQUEST NO. 831
OPERATOR RF
TAPE AX025064

T4-2
SGR126
[illegible]



1 KHz LP Filter w/ output to plotter

STRESS - KSI (AMP, P/P) vs RPM

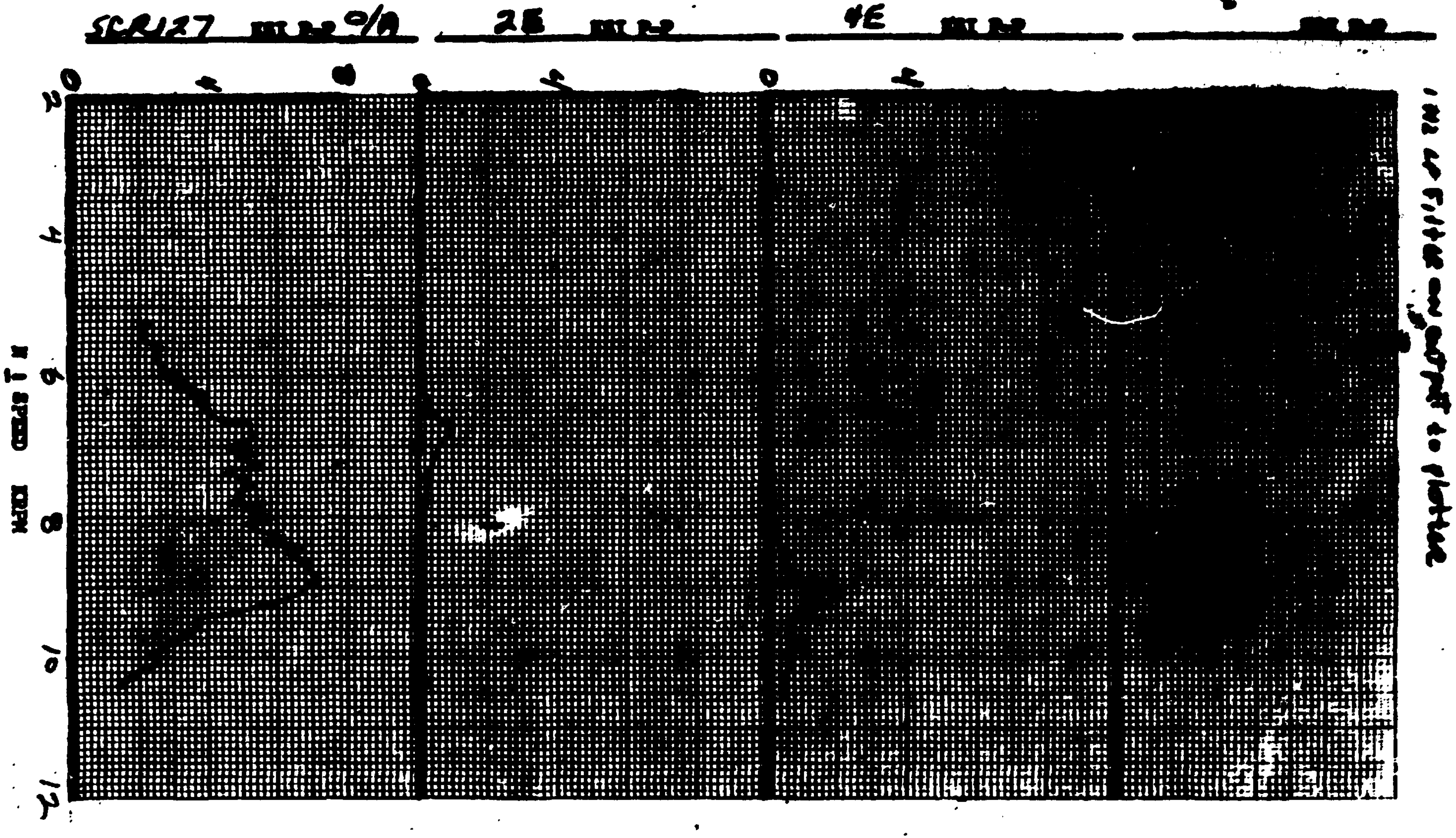
ENGINE P690
STAND A-9
CONDITION Accel EV#9

O/A KPS1 — 16KIP
3.4 ±10 Hz BW — 16KIP
TIME 10:27:25 - 10:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025064

T4-3
SCR127
⑥

3-4-5

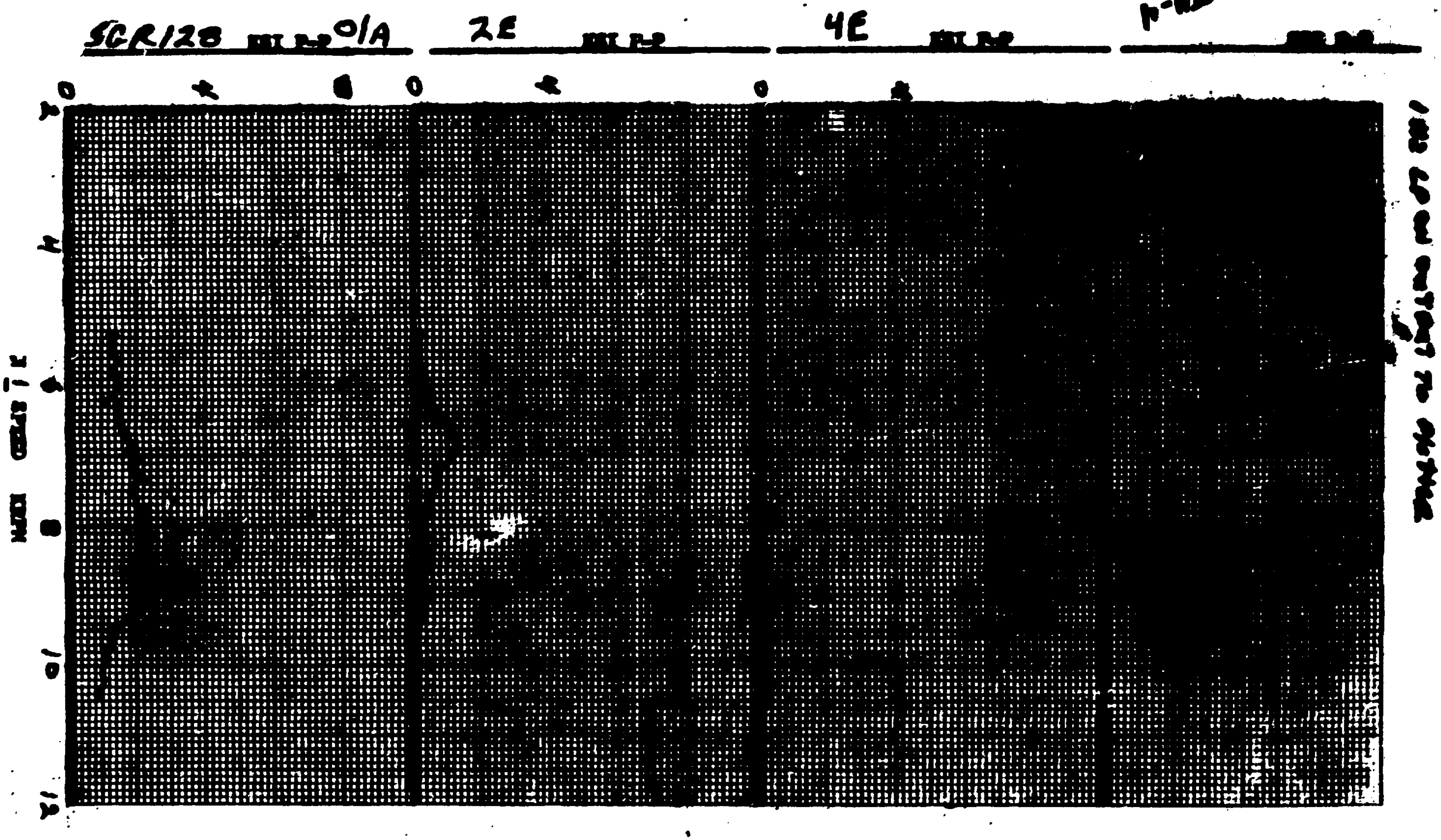


1 Hz LP Filter on output to plotter

T4-4

[illegible]

ENGINE P690
STAND A-9
CONDITION Accel EV #9
O/A KPS1 — [illegible]
3,4 [illegible] — [illegible]
TIME 18:27:25-18:28:25
REQUEST NO. 931
OPERATOR RF
TAPE AX025064



[illegible] - [illegible] ([illegible] LP/T) vs [illegible]

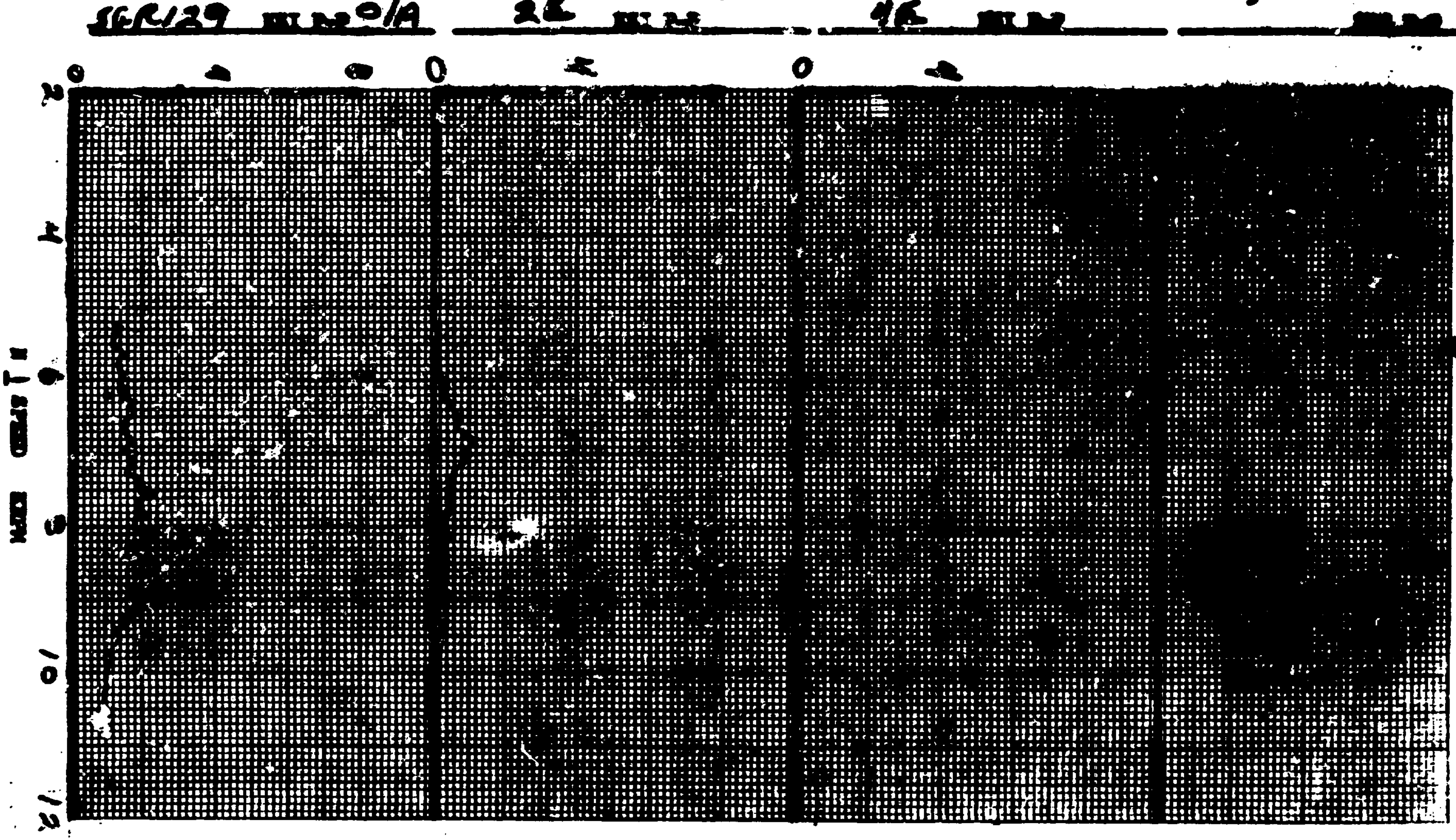
ENGINE P690
STAND A-9
CONDITION Accel EY #9

O/A KPS1 — HP 16K LP
3,4 E, 10 N2EN — HP/4K LP
TIME 18:27:25-18:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025064

T4-5
SGR129
⑤

T4-5



1 or LP Filter on output to plotter

[illegible] - [illegible] vs [illegible]

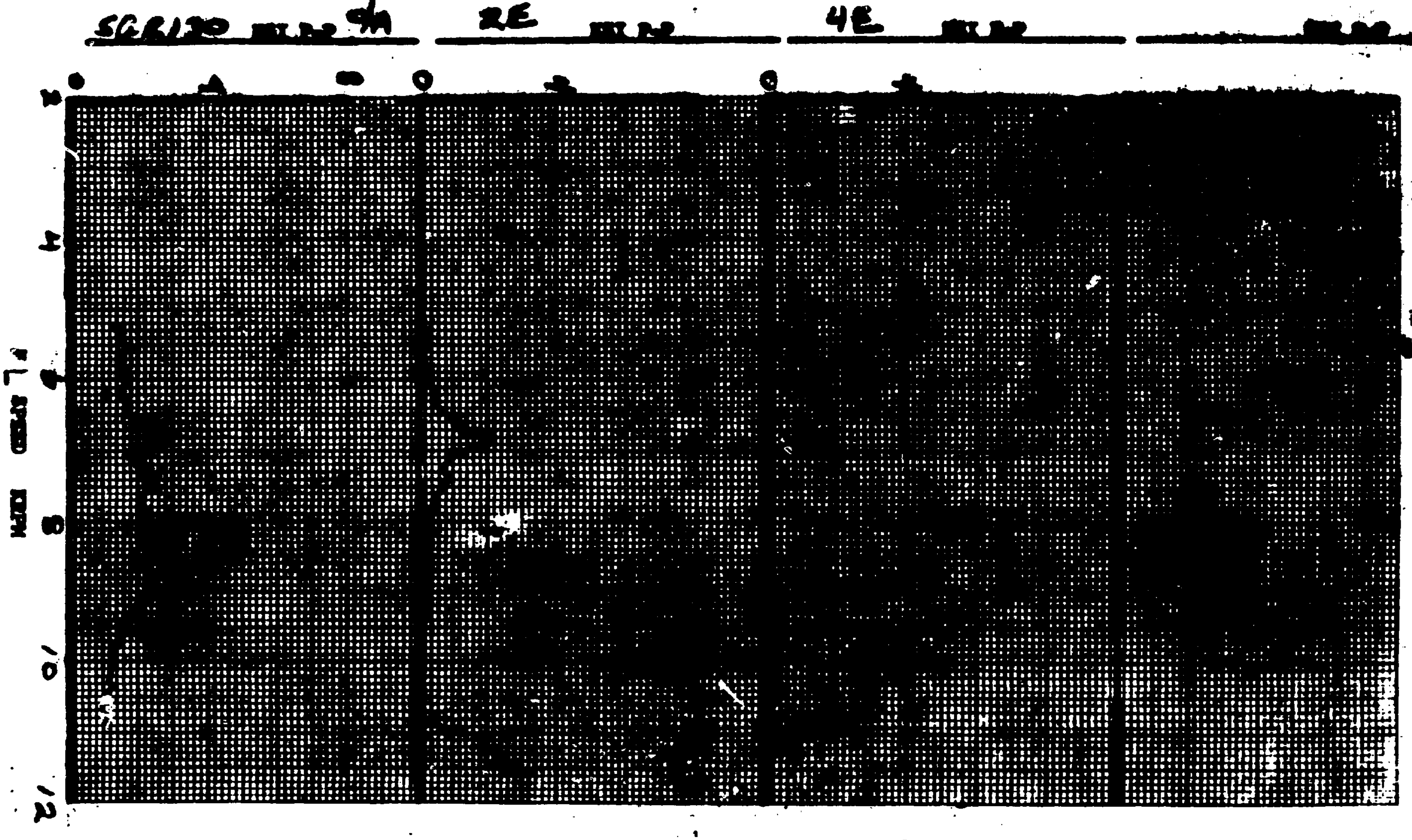
ENGINE P690
STAND A-9
CONDITION Accel EV#9

O/A KPS1 — [illegible]
2.4 [illegible] — [illegible]
TIME 18:27:25-18:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025014

T4-6
SGR130
(5)

9-hl

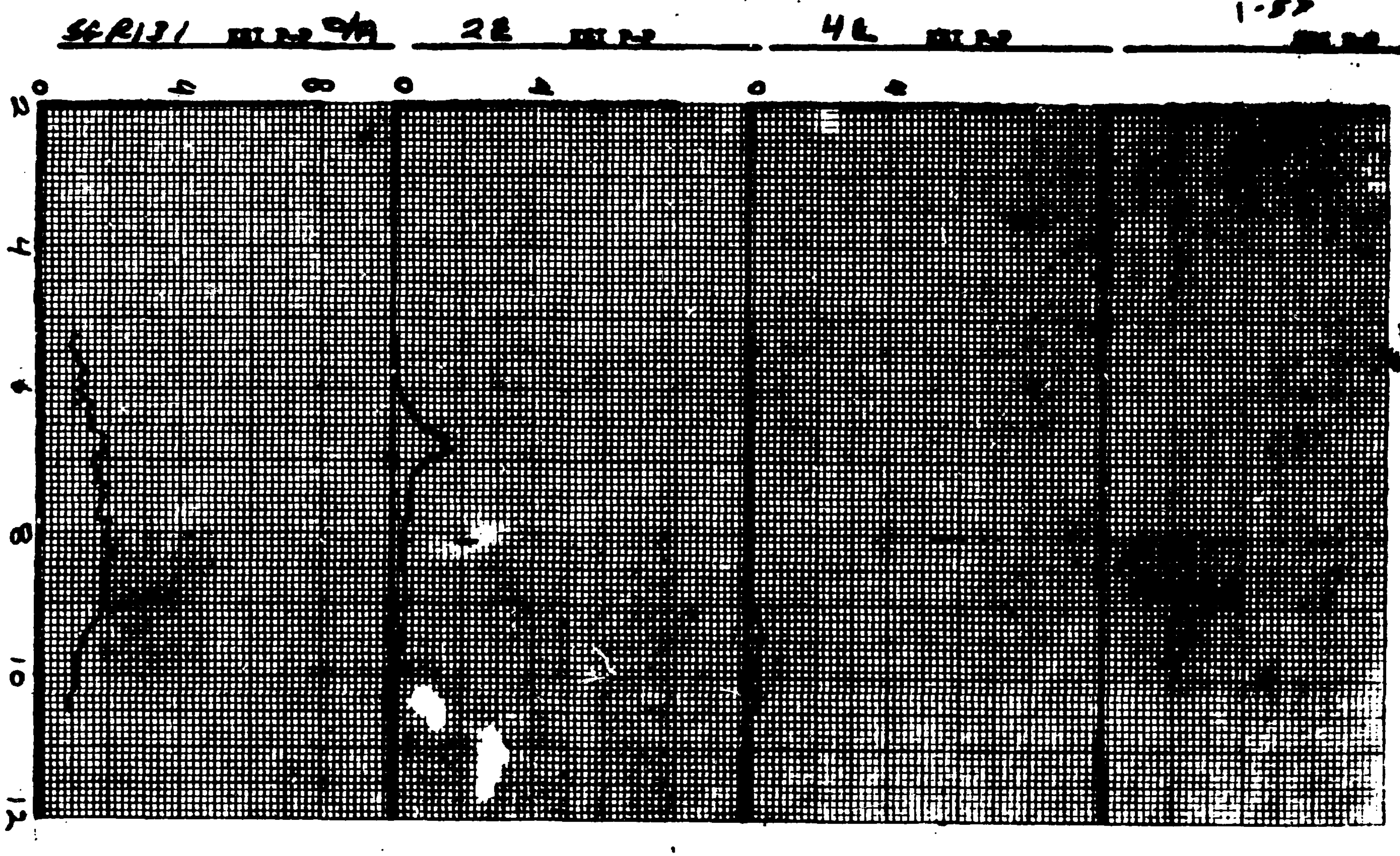


1 Hz LP filter on output to plotter

[illegible] - [illegible] ([illegible] LP/P) vs [illegible]

ENGINE P690	O/A KPS1 — [illegible] 16K LP	REQUEST NO. 831
STAND A-9	2,4 [illegible] — [illegible] 16K LP	OPERATOR RF
CONDITION Accel EV #9	TIME 18:27:25-18:28:25	TAPE AX025064

TS-1
SGR131
③



1 Hz LP Filter on output to plotter

[illegible] - [illegible] ([illegible] IP/P) vs [illegible]

ENGINE P690
STAND A-9
CONDITION Accel EV#9

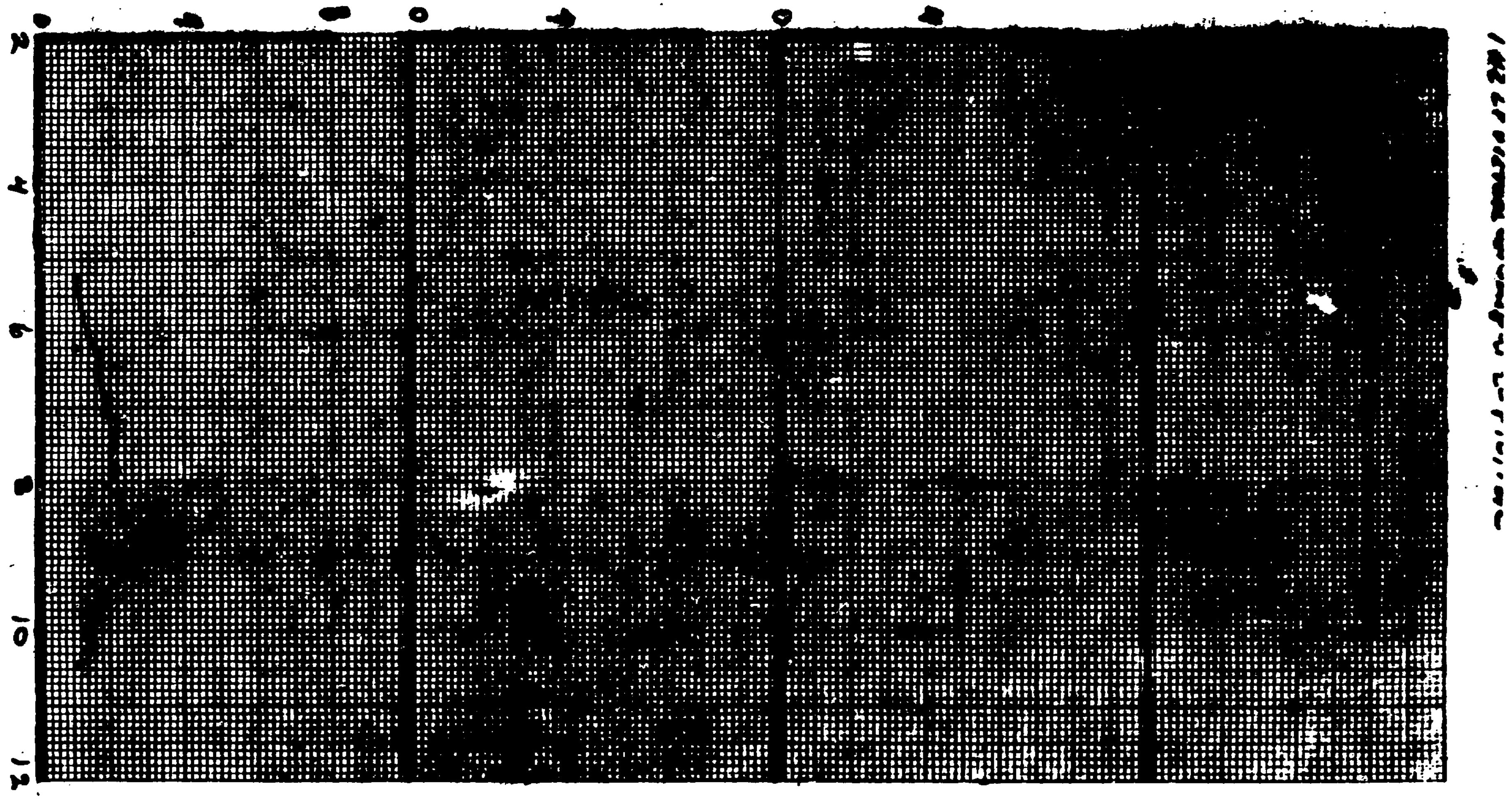
O/A KPS1 — [illegible] 16K IP
2,4 [illegible] [illegible] 16K IP
TIME 18:27:25-18:28:25

REQUEST NO. 931
OPERATOR RF
TAPE AX025064

IS-2

15-2

SR2132 [illegible] O/A   2E [illegible]   4E [illegible]   [illegible]



[illegible] - [illegible] ([illegible]) vs [illegible]

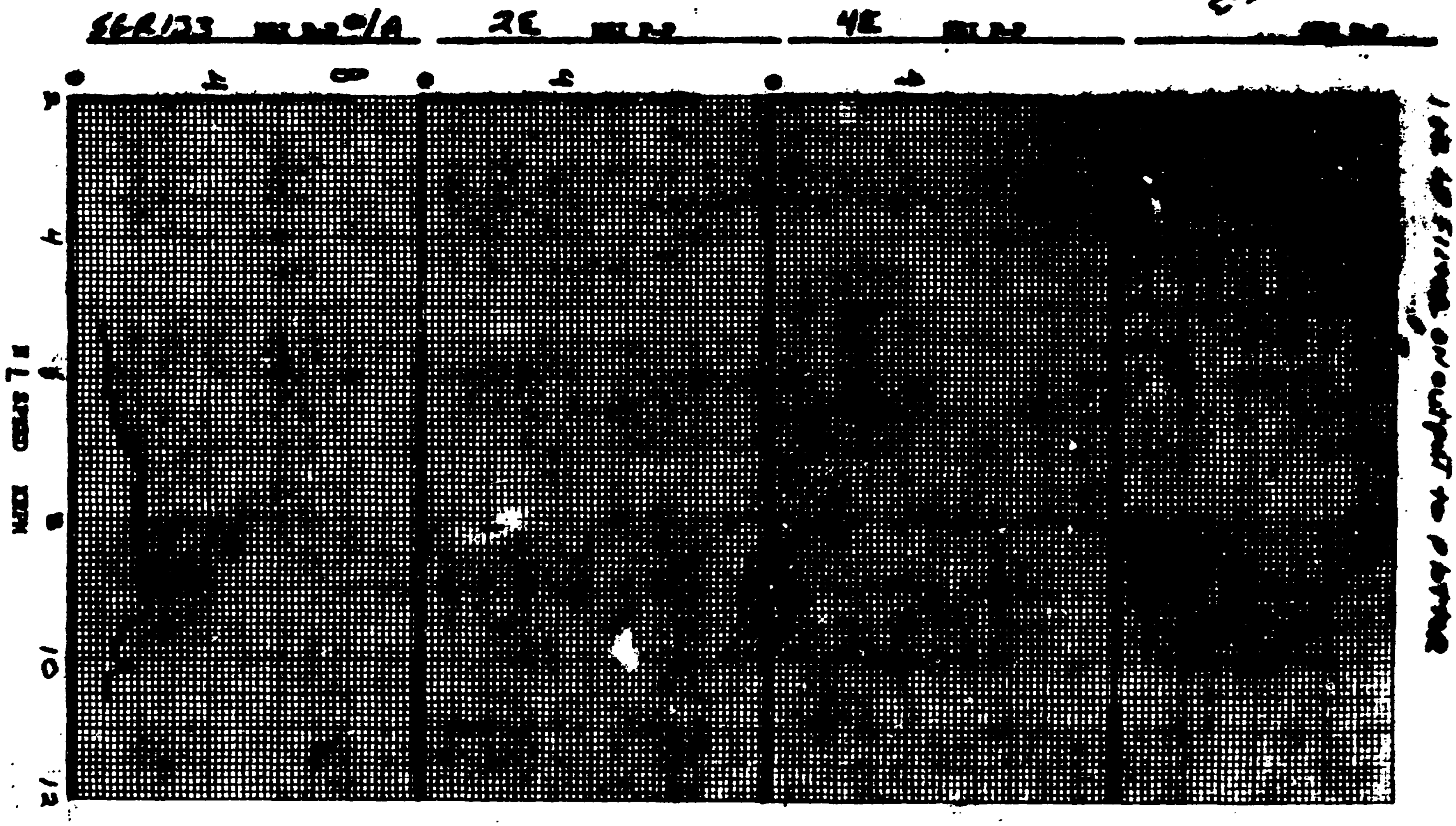
ENGINE P690
STAND A-9
CONDITION Accel EV #9

O/A KPSI — [illegible] LP
2,4 [illegible] — [illegible] LP
TIME /[illegible]:27:25-19:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AX025064

TS-3
SGR/133
③

C-5Y



1 Hz LP FILTER ON OUTPUT TO PLOTTER

[illegible] - [illegible] ([illegible] IP/P) vs [illegible]

ENGINE P690

STAND A-9

CONDITION Accel EV#9

O/A KPS1 — [illegible]/1K LP

2.4 [illegible] — [illegible]/1K LP

TIME 18:27:25-18:28:25

REQUEST NO. 831

OPERATOR RF

TAPE AX025064

TS-4

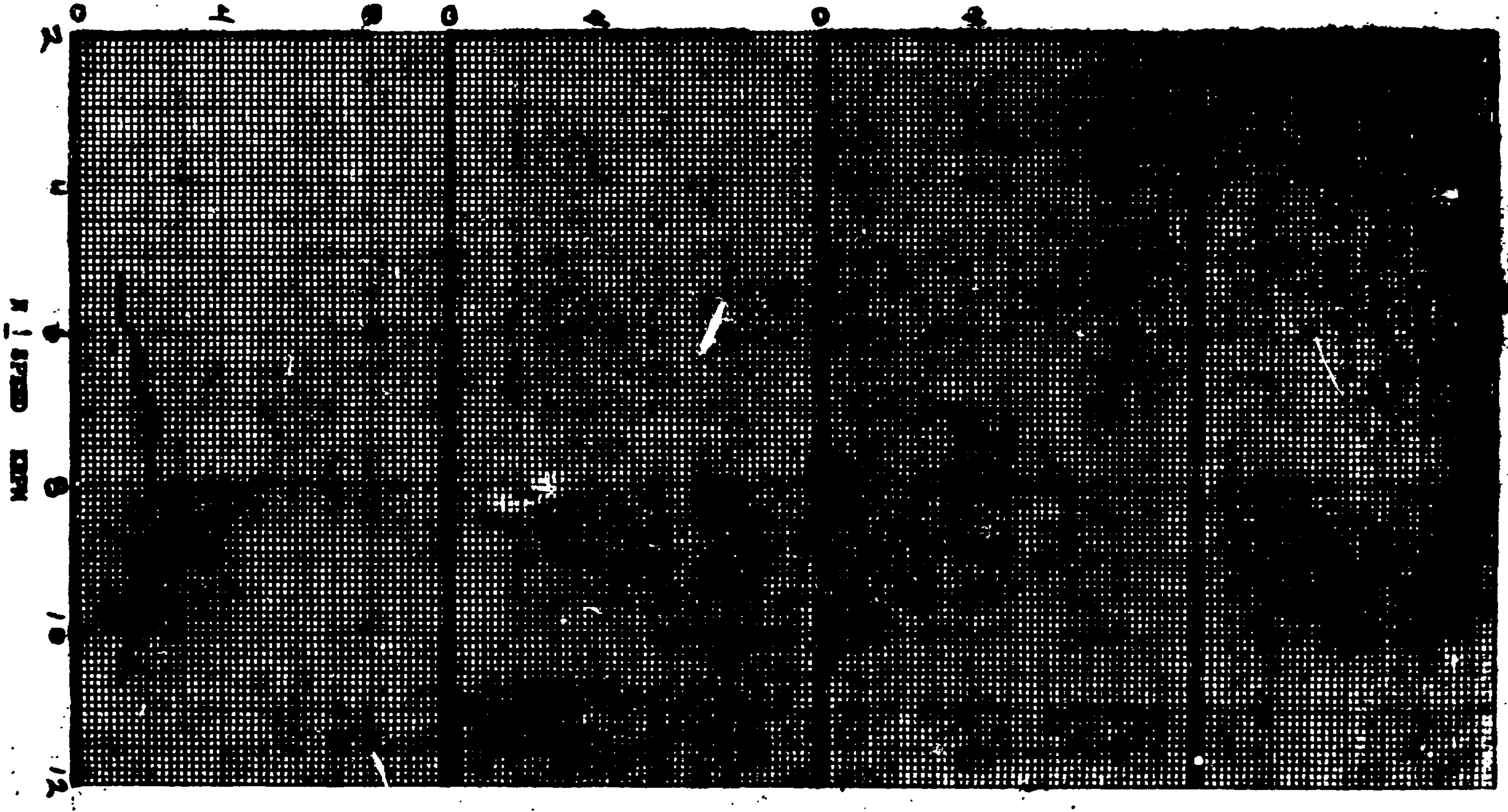
EBR134 [illegible] O/A

2E [illegible]

4E [illegible]

h-SY

[illegible]



1 Hz LP Filter on output to plotter

[illegible] - [illegible] vs [illegible]

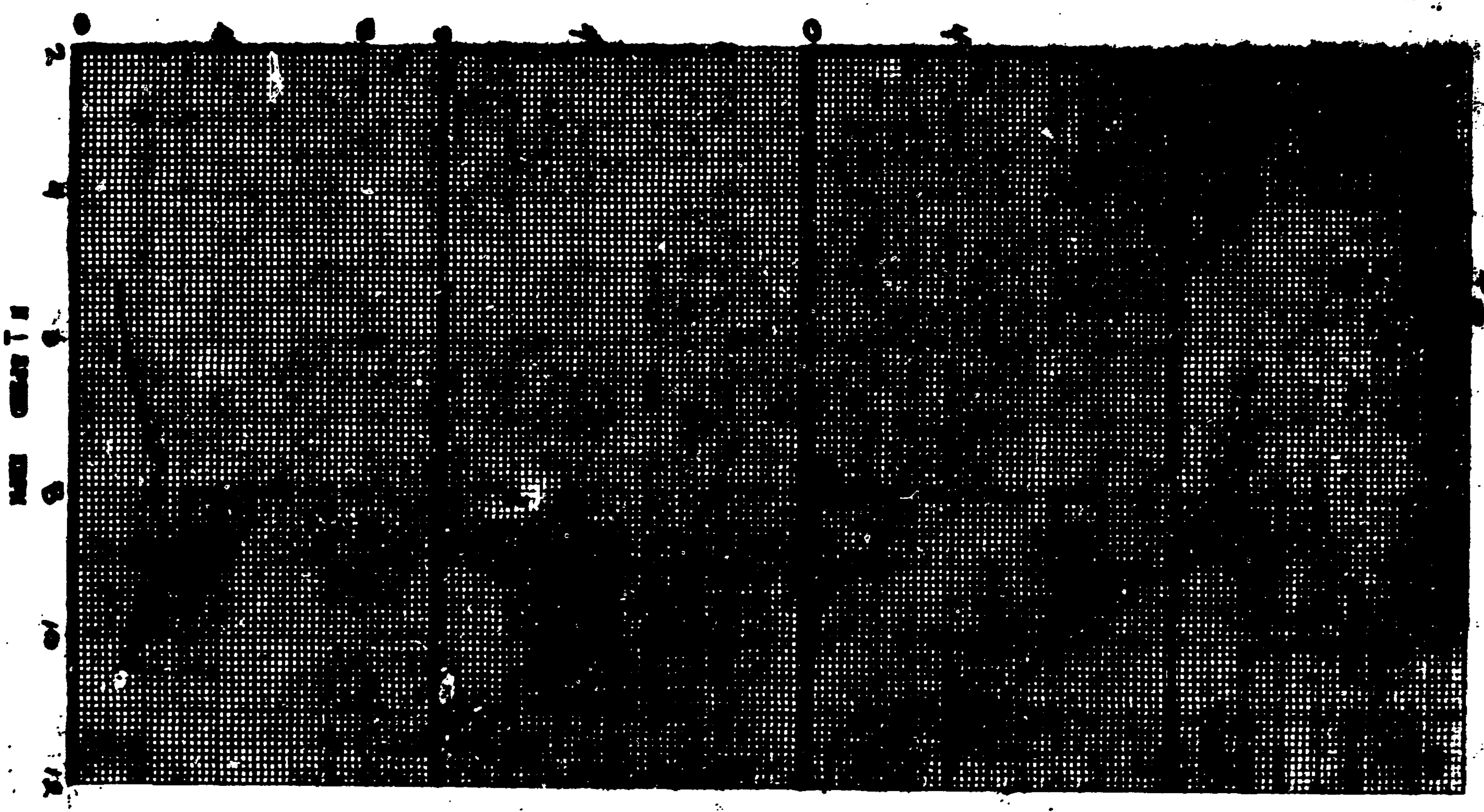
ENGINE P690
STAND A-9
CONDITION Accel EV #9

O/A KPS1 - [illegible]
3,4 [illegible] - [illegible]
TIME [illegible]:27:25-[illegible]:28:25

REQUEST NO. 831
OPERATOR RF
TAPE AK025064

9-53

[illegible]R137 [illegible] 9/A 2E [illegible] 4E [illegible]



STRESS - KSI (AVG. P/P) vs KRPM

ENGINE		O/A	KACI , 5Hz HP/6K LP	REQUEST NO.	160
STAND	A9		6 E 10HZBW — HP/6K LP	OPERATOR	RWR
CONDITION	ACCEL	TIME	18:27:27-18:29:02	TAPE	AX025064

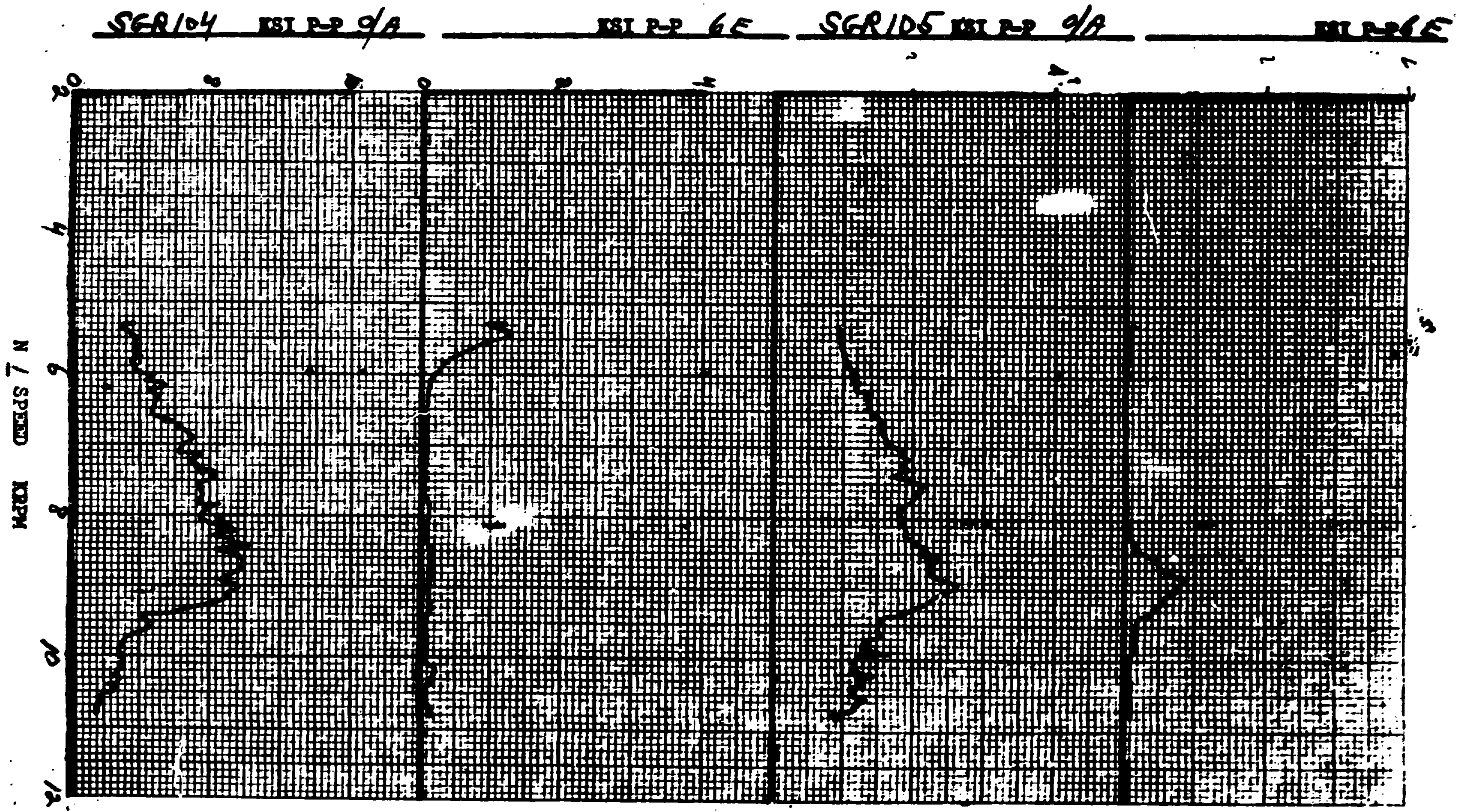
O/A + 6E

EV #9

1HZ LP FILTER

T 1/1

T 1/2



STRESS - KSI ((P/P) vs KRPM

ENGINE ____

STAND A9

CONDITION ACCEL

O/A KPSI 5HZ HP/16K LP

6E 10HZ BW - H2/16K LP

TIME 18:27:27-18:29:02

REQUEST NO. 160

OPERATOR RWG

TAPE AX025064

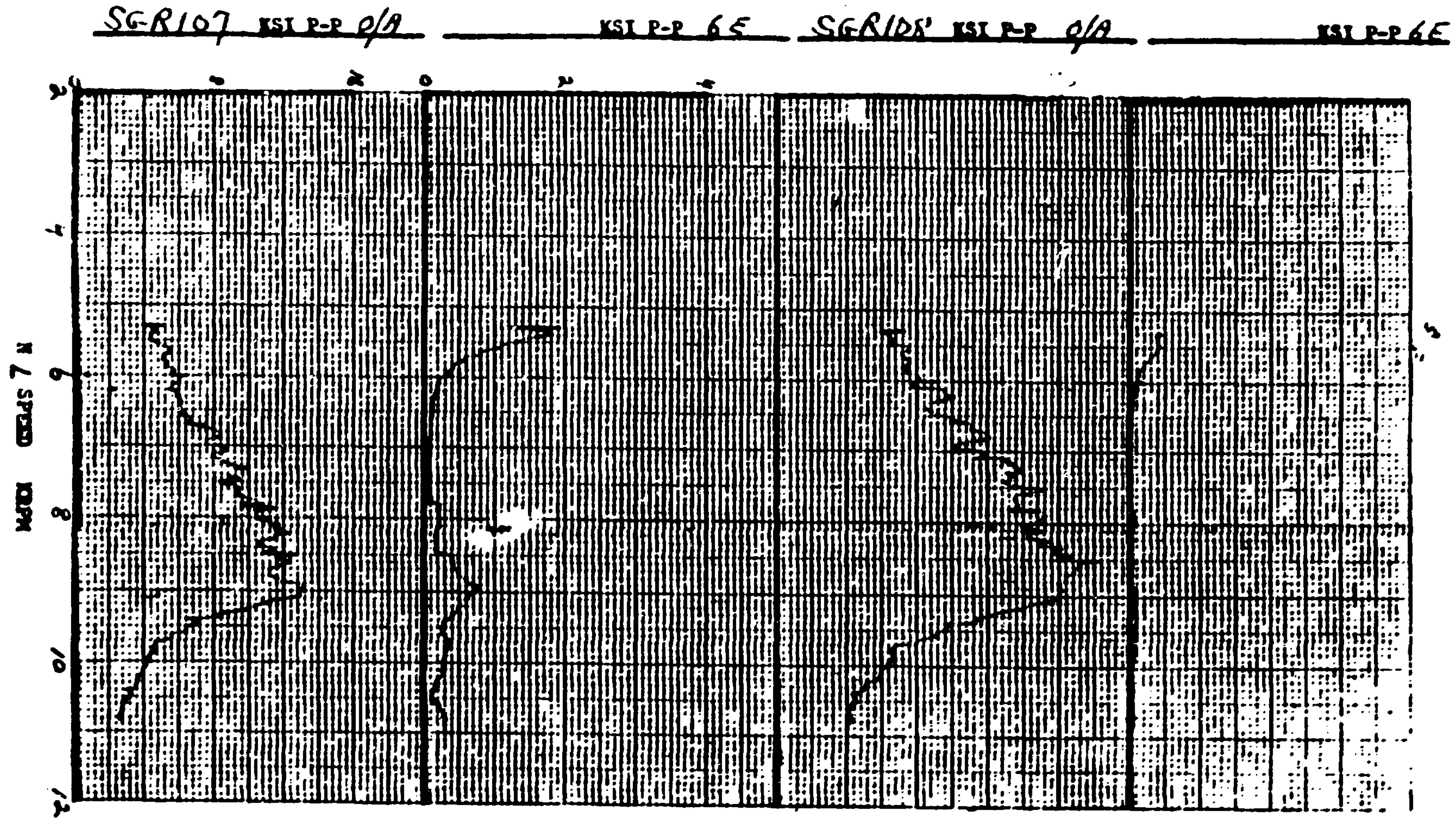
O/A + 6E

EV #0

1Hz L.P. FILTER

T1/4

T1/5



STRESS - KSI (AVG. P/P) vs KRPM

ENGINE ______ O/A KPSI 5HZ HP/6K LP REQUEST NO. 160

STAND A9 6 E 10HZ BW - HP/6K LP OPERATOR EV#9

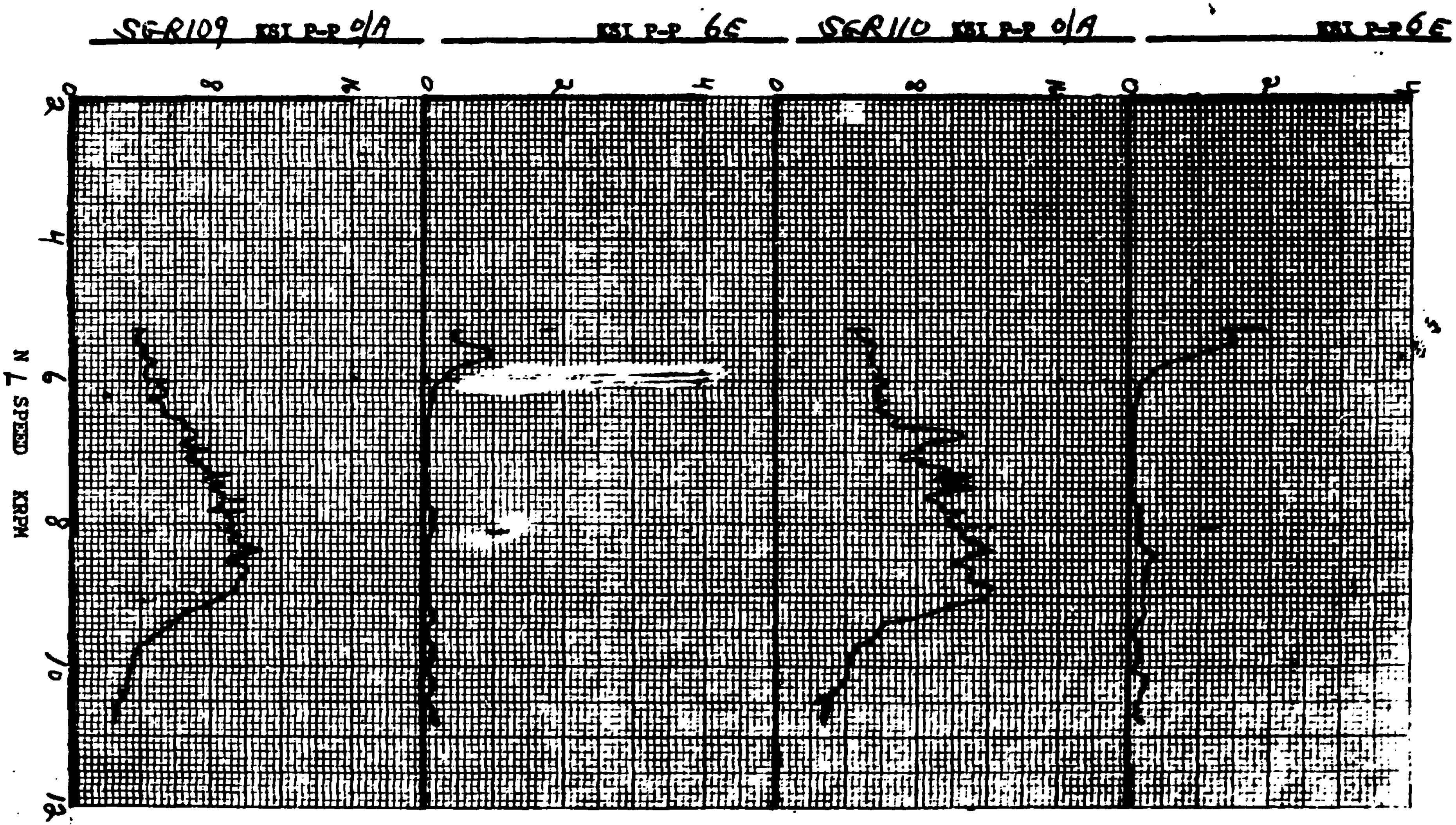
CONDITION ACCEL TIME 18:27:27-18:29:02 TAPE AX025064

T1/6 T1/7

0/A + 6E

EV#9

1HZ L.P. FILTER



STRESS - KSI (AVG. P/P) vs KRPM

ENGINE

STAND A9

CONDITION ACCEL

O/A KAST 5HZ HP/16K LP

6E/10HZBW — HP/16K LP

TIME 18:27:37-18:29:02

REQUEST NO. 160

OPERATOR EV#9

TAPE AX025064

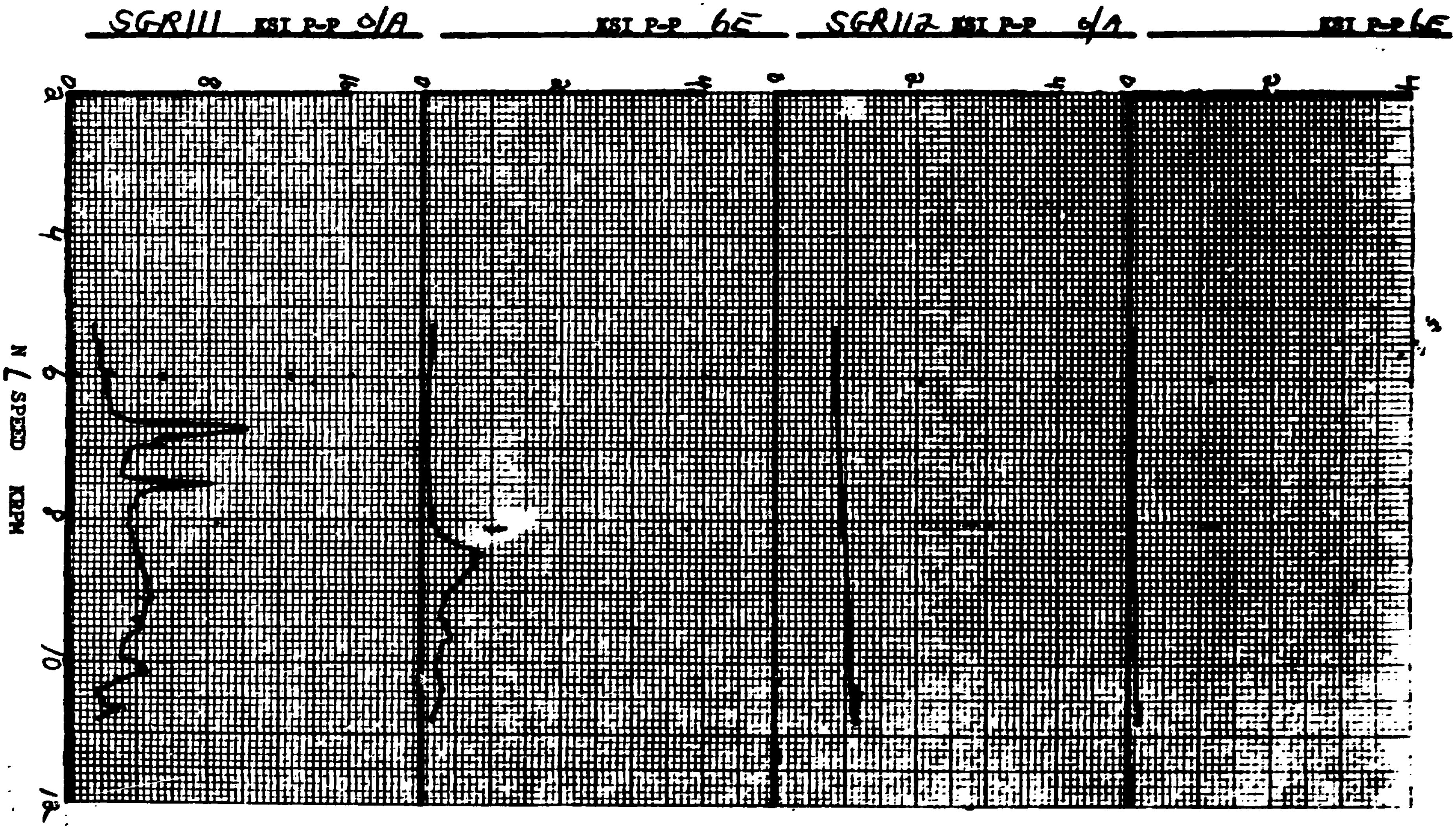
O/A + 6E

EV#9

1HZ L.P. FILTER

T2/3

T2/4



STRESS - KSI (AVG, P/P) vs KRPM

ENGINE ______

STAND A9

CONDITION ACCEL

O/A KPSI , 5HZ HP/16K LP

6E 16HZ BW - HP/16K LP

TIME 18:27:27-18:29:02

REQUEST NO. 160

OPERATOR RWR

TAPE AX025064

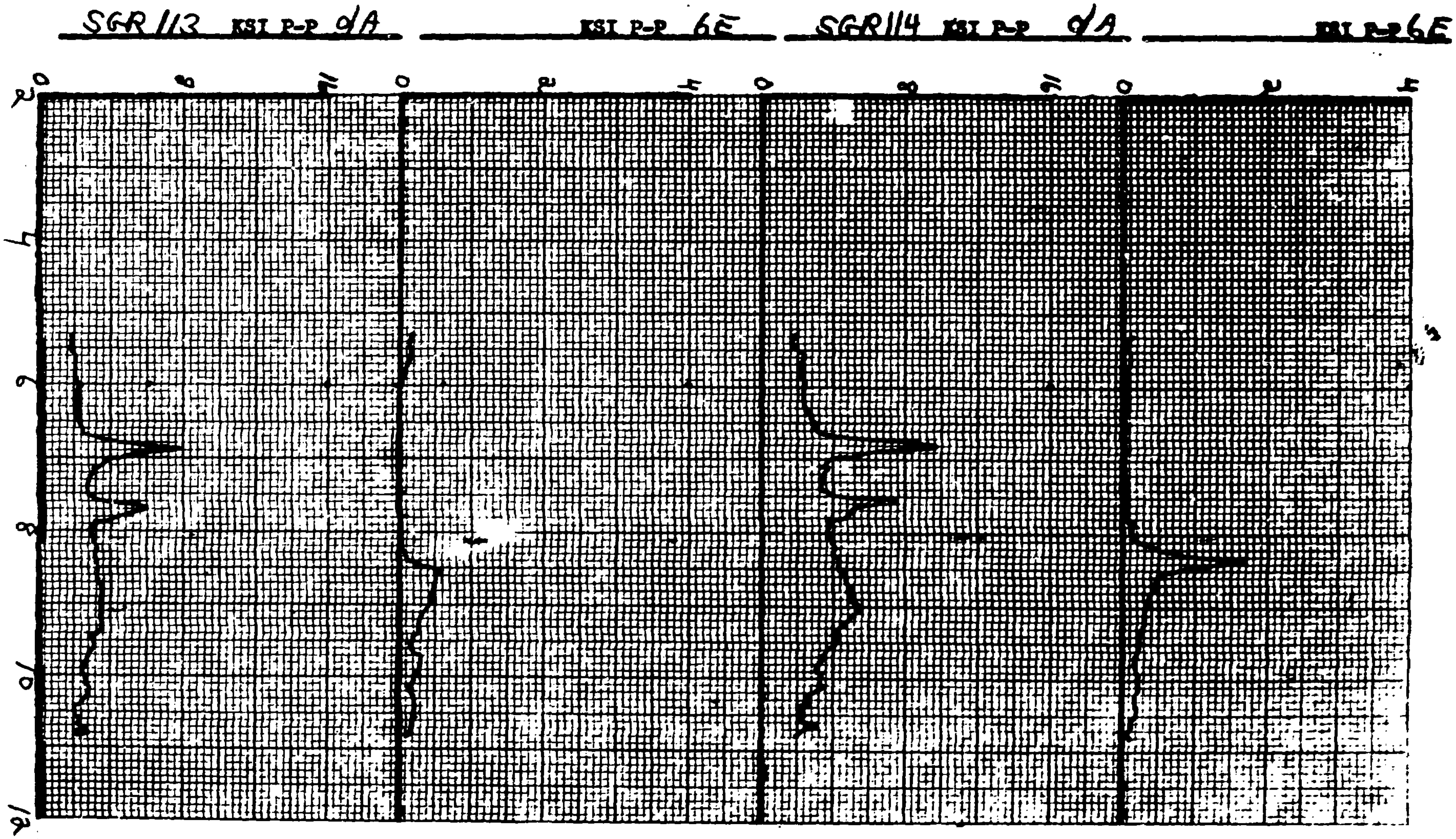
O/A & 6E

EV#9

1HZ L.P. FILTER

T2/5

T2/6



What is the enemy's doctrine?

How does the enemy prepare war plans?

What are the enemy's objectives?

What is the enemy's strategy?

What are the enemy's operational plans?

What are the enemy's courses of actions?

What are the enemy's tactics?

How does the enemy train?

How is the enemy equipped?

How is the enemy force sustained?

How is the enemy force structured?

Table 7-2. Checklist of RED Questions

What are the BLUE principles of war?

What are the friendly objectives?

What are the friendly force resources?

What is the commander's mission?

What resources does the commander have at his disposal?

What are the priority information needs of the commander?

What are the information needs to execute the mission?

Table 7-3. Checklist of BLUE Questions

8. AUTOMATED SYSTEMS

The objective of this chapter is to describe how automated systems fit into the cognitive processes of the intelligence analyst. There are a limited number of prototype automated systems that support tactical intelligence production and there are several operational systems that currently support strategic intelligence production. Many more automated intelligence support systems are in a requirements definition or development stage. The developers of these systems need an awareness of the cognitive processes of the analysts who will use their systems.

Over the course of the IMTIA study, site visits were conducted to observe and evaluate the use of existing automated systems that support intelligence production. Table 8-1 lists the systems that were reviewed during the course of this study.

SYSTEM	TYPE
BETA	Tactical, Testbed
TCAC	Tactical, Development
ITEP	*TENCAP
DITB	*TENCAP
AMH	Strategic, Operational

Table 8-1. Reviewed Systems
*TENCAP - Tactical Exploitation of National Capabilities

Users, developers, and trainers were interviewed with respect to how analysis was affected by the existence of these systems. The intent was not to study the performance of these systems but to understand how automated supports relate to intelligence analysis.

The observations from these site visits and interviews were integrated with our own experience with automated systems and compared with the implications of the cognitive model. As a result, we have compiled a set of conclusions about common design problems in existing systems and implications for future automated systems.

8.1 Common Problems

In the past, automated systems have been developed with the objective of exploiting some form of data processing functionality (memory, computation, communications) without a clear understanding of how the system will affect the performance aspect of analysis. Many of the problems these systems have experienced in the area of user acceptability appear to be traceable to the lack of understanding of the human performance aspects of intelligence analysis on the part of the system developers. In looking at the information architecture of these systems in relation to the cognitive framework, there are several common inconsistencies that may be the source of usability problems. Four of the most important inconsistencies are:

- The structural features of the automated data base do not match the structure of the analyst's threat model.
- The user interface dialog does not provide for separating the contexts of different users in different roles or different objectives in multiple analysis tasks.
- Display and control arrangements are not tailored to various thinking skills or to variations in skill within the user population.
- Feedback mechanisms between information sources, analysts, and product users are not integral to the system architecture.
- Communication mechanisms in automated systems do not fully exploit the value of shared conceptual models.

These problem areas are further defined in the following paragraphs.

8.1.1 INCONSISTENCIES WITH THREAT MODEL

The threat model is the analyst's means of seeing the battlefield through an abstraction of perceived reality. The threat model is an integrating framework that facilitates multi-source exploitation and multi-disciplinary analytical team effort. Most database aids in automated intelligence support systems address some aspect of threat model information (e.g., order of battle, operations plan, terrain, weather). Current systems have database structures that are inconsistent with the threat model in one or more of the following ways:

- The data cannot be tailored to the mission context.

  Information, such as order of battle, is sensitive to the mission context and environmental factors. Multiple representations or adaptivity features are required to tailor the threat model data to a particular situation.

- The data cannot be easily related to a specific time-space framework.

  All threat model information must be placed in the time-space framework relevant to the mission.

- Data are not classified as hypothesis vs. observation (facts, evidence).

  The entire threat model is a hypothetical structure. The hypothetical structure provides the means of interpreting new information. The hypothetical structure should be distinguishable from the information gathered to substantiate or repudiate the hypothesis.

- Data cannot be selectively displayed (using geographic boundaries, time window, entity class, or entity parameters) as selection criteria.

  The totality of threat model data requires that mechanisms be used for decluttering the user's view of the threat model. Selective retrieval and display is a required for effective use of a threat model database.

- Data cannot be portrayed from different perspectives.

The threat model has three major perspectives -- WHITE, RED, and BLUE. In addition, specific uses of threat model information may require varying levels of detail or resolution. The ability to shift perspectives enables the analyst to deal with much more information than is possible with a single perspective.

- Information cannot be dealt with in sets.

  Within the battlefield, there are numerous objects that can be treated as members of a class (e.g., type of unit or equipment) or set (e.g., force composed of individual units, communication net, command structure, events occurring in line of communication). Databases must be able to recognize the association of objects or information events as part of a set.

8.1.2 LACK OF MULTI-PROCESSING SUPPORT

Automated systems in general are not structured to support the multiple processes of the total analytical procedure. On the surface, analytical procedure appears to be data driven. Most ADP systems have assumed a data-driven interaction, either by incoming raw intelligence messages or by commands from the user. The IMTIA cognitive model has shown the analytical process to be objective driven, but with interruptions driven by opportunities to exploit information sources. For an automated system that hopes to follow and aid the analytical procedure, there must be provisions for supporting multiple on-going analytical processes that run concurrently and that interrupt each other.

Because most system designers have not been aware of a common structure in the analytical process, there has been no attempt to support that structure or the processes that occur within that structure.

8.1.3 COMPENSATION FOR USER SKILL LEVEL

Little attention has been given in current systems to varying skill levels in the user population. Intelligence analysts represent many different skill levels because of personnel rotation, rank, discipline, education and experience. A system designed for the casual user may be cumbersome and frustrating for the experienced user. A system that can only be operated by an experienced user places inordinate demands on training resources and risks failure under the stresses of battlefield or crisis situations.

Systems that deal with the issue of varying user skill levels are more difficult to design and guidelines for dealing with this issue have not been available.

8.1.4 LACK OF FEEDBACK MECHANISMS

The IMTIA study clearly identified the role of feedback in the communication processes between the analyst and the intelligence user and between the analyst and information sources. Because most of the feedback channels are informal in non-automated intelligence production systems, the feedback mechanisms may have been overlooked by the developers of automated systems. Feedback is an essential feature in controlling information overload from collection system inputs and in the generation of quality intelligence products. Feedback is the natural mechanism that the analyst uses in tailoring intelligence products to the specific needs of user. Because feedback mechanisms operate over a long period of time, its importance is not apparent in systems with stable configurations and operating procedures. However, in a dynamically-changing battlefield environment, crisis situation, or in newly formed analytical teams, the criticality of feedback is more apparent.

8.1.5 COMMUNICATIONS WITHOUT SHARED CONCEPTUAL MODELS

The most critical problem in tactical intelligence production is communications. Tactical communications are vulnerable to jamming, environmental factors, fires, overloading, and disruption during maneuver. Because of these factors, tactical communication channels do not have predictable bandwidths, availability, reliability, and throughput times. Strategic communications as well may be affected by delays caused by peak period overloads, manual handling, and misdissemination of messages. None of the ADP systems reviewed addressed the problem of achieving effective communications under these conditions.

The observation of informal communications in analyst activities has shown that there are natural mechanisms for dealing with the problems of unreliable communication channels. These mechanisms exploit shared conceptual models as discussed in Chapter 3. Automated communications have not yet been designed for exploiting the concept of shared conceptual models. Common problems are that more data are sent than needed, or critical data needed to establish a context for interpretation are missing.

Communications designs do not use a cognitive framework for deciding the relative importance of information; under adverse communication conditions the most important information does not always get sent first.

8.2 Reviews of Intelligence ADP Systems

The reviews of automated systems conducted under the IMTIA study were not aimed at evaluating the performance of the automated data processing functions. The objective was to look for successes and failures that were related to human cognitive processes.

Current systems are designed with the primary objective of exploiting sensor, communication, or adp technology rather than aiding the cognitive processes of the user. User interface configurations are designed in an ad hoc manner and do not reflect a systematic application of design guidelines (primarily because adequate guidelines have not been available). As such, instances where automated systems successfully support the cognitive processes of the analyst are largely due to the intuition of the designer or have evolved with operational experience.

Failings in many cases could have been avoided with the application of guidelines that addressed the issues of cognitive performance.

A synopsis of the system reviews is provided below to illustrate some of the critical issues in future system developments.

8.2.1 BETA

BETA was designed as a testbed system to demonstrate the utility of multi-source intelligence exploitation for targeting and situation assessment.

One of the most important features of BETA is its capability to allow users to selectively call up and display information from the shared database. Each user's display can be scaled to the geographic area of interest and can display battlefield entities selected by by class, by time parameters, and by specific attributes of the entity. The selective display features are controlled by the user through the use of query structures that act on a shared database.

In essence, the BETA user display is adaptive to the role and interests of the user. The BETA user command language, however, is not adaptive to the role and skill level of the user. Although the use of menus and forms makes it possible for a relatively inexperienced user to exercise the system functionality, the interactive dialog can be very cumbersome for the experienced user.

BETA lacks desirable feedback mechanisms on what the automatic correlation algorithms are doing and lacks easily modifiable templates for entities represented by the system.

An important feature of the BETA system is that it provides graphics communications for conveying the results of target analysis and situation assessment.

Many of the functions of BETA map into the idealized threat model structure presented in Chapters 6 and 7. The most important feature missing from BETA's threat modeling capability is the lack of time snapshot partitioning. The user is unable to "back up" the displayed time window or "project" a future time snapshot. This missing feature makes it impossible for the user to go back and reinterpret sensor reports against a new hypothesis or to project an outcome of a situation.

8.2.2 TCAC

Very little information was available on TCAC at the time of the IMTIA system reviews. Comments made by analysts during interviews reflected a common concern about TCAC's lack of a geographic framework as an integral part of its display capability. The implications of the threat modeling study are clear about the need for a geographic framework in all forms of tactical and strategic intelligence analysis.

8.2.3 ITEP

ITEP is a product of the TENCAP Program. TENCAP (Tactical Exploitation of National Capabilities), is a program designed to provide access to National Technical Means intelligence products at the tactical level. ITEP is an interim system that was designed to exploit ELINT intelligence.

Clearly, the most important issue demonstrated by ITEP is the need for the analyst's involvement in the system development process. ITEP is regarded by users as a very successful development effort. Much of ITEP's success is attributed to the heavy involvement of intelligence analysts in evolving the functional features and interactive capabilities. The user interface is highly interactive and the analyst is involved in all analytical decisions.

The user interface is not designed for a casual user.

8.2.4 DITB

DITB is another product of the TENCAP program that is aimed at imagery exploitation. This system demonstrates the importance of sharing information on collection plans and requirements in order to fully exploit intelligence gathering resources. DITB as well as ITEP demonstrate the utility of reducing the time delays in dissemination of collected intelligence.

8.2.5 AUTOMATED MESSAGE HANDLING

The bulk of raw intelligence data and many intelligence products are carried through the media of digital communication networks as electrical messages. These networks also carry requirements, queries, and responses as messages. Automated message handling capabilities were introduced into the intelligence environment during the 70's to deal with the problems of increasing message volumes, manual handling delays, crisis peak loading conditions, new requirements from new collection capabilities, and need for more rapid and accurate dissemination.

Automated message handling systems also make it possible to provide direct updates to intelligence community databases such as DIAOLS/COINS.

Automated message handling capabilities were first introduced at the CIA and DIA and subsequently to military commands. AMH is gradually being introduced into the tactical environment starting with Echelons above Corps.

The most important cognitive aspect of these automated message handling systems in intelligence is that dissemination is controlled by user interest rather than by distribution list assigned by the sender. Dissemination control is exercised at the receiving end rather than the transmitting end. This is an extremely important characteristic of intelligence distribution that facilitates the exploitation of all sources of information.

Intelligence analysts need to be in control of the information-gathering process. The ability to select information from the electrical message carrying networks by automatic filtering is a critical capability required to cope with information overload in the modern intelligence environment.

8.3 Future Implications

The results of the IMTIA study have direct implications for the design of future automated intelligence support systems. The general implications are:

- The threat model can be used as a guideline for the organization of database structures to support the intelligence analyst.
- The steps required to build the threat model can be used as a checklist for functions required to support the storage and retrieval of intelligence data.

- The design of interactive dialogs must take into account the multiplicity of analysis tasks. Each analysis task carries with it a different objective, differing information needs, and differing procedure requirements.

- Analysis tasks adapt with the changing mission needs. Automated aids that support the analyst in meeting mission information requirements must be adaptable to the mission parameters.

- The nine thinking skills in the cognitive procedure provide a framework for the design of an interactive dialog between the analyst and the automated support system. Each skill provides a focal point for the design of display and control features of the user interface. The general sequence in which these skills are performed provides a prototypical order for automatic sequencing of machine-initiated help or cognitive aids. Sequences can be named and identified with the context of a particular task/mission so that sequences can be interrupted, saved, resumed, or repeated automatically.

- The IMTIA model of communications is a model of normal informal communications. The analyst in day-to-day activities uses shared conceptual models as a foundation for communications. Informal communications are extremely flexible in adapting to media and time constraints.

  Day-to-day interaction between parties establishes a broad base of shared conceptual models. In informal communications, once a context has been established, the actual information exchange can be very brief but achieve a high level of understanding. This is especially important when the time available is extremely limited.

  Automated systems can be similarly designed by organizing information into context-specific networks (e.g., artillery targeting, EW targeting, weather, OPSEC, etc.) Many context-specific networks can be mapped onto a single digital message network. Modern communications protocols can be utilized for error control and allocating available bandwidth between the multiple networks.

  Automated communications should be based on exploiting the nature of shared conceptual models in order to achieve understandability and effectiveness. Designers must recognize the multiplicity of the information networks that permeate intelligence operations, each using different conceptual models of the real world. Because of the multiple contexts in which the same information may be used, communications designers must recognize the need to tailor information to a particular user or usage. Although the number of logical networks may be more numerous under this approach, the actual data transfer rates can be minimized by exploiting existing shared knowledge between sending and receiving parties that is context dependent. Communications systems that do not exploit context must transmit substantially more data in each message to convey the same amount of information.

The use of a cognitive framework for the design of the user interface is being pursued under an on-going research project sponsored by ARI. (Research on Human Factors in Design for C^3I, Contract No. MDA903-81-C-0579.) This research effort is aimed at developing guidelines for system developers who wish to incorporate adaptive user interface features.

9. RESEARCH, DEVELOPMENT, AND TRAINING ISSUES

The eight previous chapters have summarized and discussed current cognitive issues in performing intelligence analysis. Some of these issues have direct implications for training; others raise questions that require further research and development. Further research would in turn provide clarification and understanding that would be applicable to improved training methods.

9.1 Cognitive Processes

Some important problems raised in analyzing and evaluating cognitive processes and performance in intelligence analysis are described below.

9.1.1 TASK SEGMENTS AND SKILLS

While the task segments underlying analytic performance have been identified, the actual cognitive skills required to execute the task segments have not been itemized individually. The general skills described in Chapter 4 apply to all task segments. As described in Section 7.1, it is hypothesized that there exist very specific cognitive skills pertinent to the individual task segments. These should be identified individually and training materials developed, tailored to the individual task segments.

The different task segments are associated with different biases and are differentially affected by the cognitive biases discussed in Section 2.4. The relationship betwsen task segments and biases should be investigated. Such an investigation could begin with a case study review of intelligence products to identify where and how cognitive biases might have led to misleading or erroneous predictions or situation assessments.

9.1.2 TRAINING IMPLICATIONS FROM THE COGNITIVE MODEL

The various aspects of the cognitive model, as described in Chapters 2 through 5 have numerous implications for training.

Because of the importance of decision making in intelligence analysis, it is imperative that more research be devoted to the types of decisions that analysts have to make, how they make them, and how they affect the intelligence product. This would be a high pay-off area for research, since analytical thinking covers an extremely broad and complex domain. Though much is known about decision theory and rules for application, it would be detrimental to train analysts using extant knowledge in decision theory and by providing them with a few formal rules without first investigating the context and contents of analytic decisions.

While there exist numerous automated and non-automated decision aids, many of these aids are not appropriate for intelligence analysis because the quantity and quality of information necessary to utilize the aids in the intelligence arena is not available. However, there exist certain recurrent problems encountered when making decisions in the intelligence context that are tied to limitations of the human information-processing system, and there are fundamental procedures that would prove useful in dealing with these problems.

The development of effective analytical thinking is likely to proceed through experience with relevant classes of examples. From such experience will emerge an awareness of common pitfalls inherent in analysis as well as procedural guides and decision paths to maximize the quality of performance. Toward this goal, a selective list of fundamental concepts and problem areas in the context of operational intelligence could be prepared for inclusion in a training program. Also, a limited set of examples could be developed such that useful guides (procedures) for dealing with the problem areas can be illustrated and imparted effectively to the analyst trainees. The suggested procedures would serve to develop a general attitude about problem solving and decision making that is conducive to optimizing analytical thinking. Although the trainee may never encounter the precise events described in the examples, experience with the important problem areas and useful modes of solution (the analytical processes) should generalize to a broad class of similar situations.

Among the concepts and problem areas in analytical thinking that should be considered for inclusion in a training program are:

- Inflexibility of thought (cognitive entrenchment, e.g., confirmation bias).
- Separation of relevant from irrelevant information (e.g., unwarranted hypothesis switching).
- Filtering biases (selectivity, polarization).
- Interpretation of sparse or uncertain data (caricature effect).
- Memory access shortfalls (similarity effects).
- Information management (summarizing, sorting, assessing trends, checklists, memory aids).
- Fallacies of logic (e.g., the "gambler's fallacy" in prediction).
- Asking the right questions (recognizing goals).

Among the general decision guides to analytical thinking that might be addressed are:

- Seeing the total picture (avoiding over-focusing on details).
- Withholding judgment (hypothesis testing as an iterative process).
- Using models (doctrine, templates, prototypes).
- Generating hypotheses based on partial information.
- Changing perspective (restructuring problems).
- Understanding uncertainty and reliability (will to doubt).
- Using stable substructures.
- Discussing problems and decision alternatives with others.

9.2 The Analyst/User Dialog

The importance of communication in general, and between analyst and user specifically, should be explored more thoroughly. Ways to optimize the development and use of shared conceptual models to enhance communication and reduce errors and misunderstandings should be investigated. There are two parallel areas of inquiry relevant to communication, namely by:

- Types and areas of communications (e.g., which ones are most important, which ones might increase danger if misunderstandings occur).
- Types and areas of misunderstandings that are known to occur.

Inquiries should begin with interviews and result in lists, hierarchically organized by importance, of these two areas. Among the specific issues to be investigated are the following:

- The analyst must have an adequate understanding of how the intelligence product will affect the user's perception of threat. We know that the desired reaction is for the user to perceive an increased level of control and a reduction in danger. The first research question, therefore, concerns the measurement requirements for determining any changes in the analyst's and the user's perception of threat.
- Current feedback to analysts is generally informal or non-existent unless the analyst is in direct contact with the user. Feedback mechanisms are required for the analyst to know if these effects are being achieved. The following questions should be investigated:
  - What are optimum feedback mechanisms?
  - How can they be exploited?
  - How can their effectiveness be measured?
- Shared conceptual models have the potential for being exploited to reduce errors and costs of battlefield communications, as well as for improving the commander's timeline for control. Ways of measuring the efficiency of SCMs are needed to justify revamping current communications concepts.

  There are several research questions that deal directly with the way SCMs, as well as CMs, are generated and used in information processing, analysis, and communications:

  - What are the characteristics of the cues that allow for the "best" (most complete, most appropriate) retrieval from external memory?
  - What knowledge items do we need within our own CMs in order to make use of external memory?
  - What are the best retrieval cues to access other CMs within one's own memory or to access external memory? Are they the same?
  - What types of informational items *have* to be shared for SCMs to be optimally effective? Intuitively, one might suggest the following as important common factors for effective SCMs:

    - Context, framework.
    - Goals.
    - Language.
    - Affective value of CM.
  - How can effective SCMs be generated?
  - How can the effectiveness of SCMs be measured?

If some of these questions could be determined, then training materials could be structured so as to include appropriate information to generate SCMs and appropriate retrieval cues for correct access to internal and external memory.

Summary Questions on research involving SCMs include:

- How are SCMs established and can the process be speeded up?
- How can the shared aspects of conceptual models be identified?
- How can areas of misunderstanding be identified?

9.2.1 *IMPLICATIONS FOR TRAINING*

The views presented here concerning CMs, SCMs, and goals, have several important implications for understanding learning, retention, and recall, and hence, for the development of training materials, for education, for training new skills, for the maintenance of skills, and for improving communications within the intelligence community.

Some of these implications are as follows:

- It is important to develop a common framework among analysts concerning the goals of analysis, its organizational basis, and its role within the military community and for the overall goal of national defense. This framework should be shared at all levels of analysis (horizontally and vertically) and it should be shared with the users.

  Developing such a framework has two consequences:

  - It provides the new analyst with an organized structure (a new CM in memory) within which to store new learning materials. The alternative is that new materials must be stored in existing CMs, carried over from earlier training. These existing CMs may be quite inappropriate for organizing new materials, and the result is confusion and/or slower learning.
  - It sets the context for establishing SCMs between analysts, and it provides the basis for the analysts themselves to establish SCMs with their clients.
- The goals and subgoals of analysis should be clearly spelled out and invested with affective values so as to increase the importance (and hence, the speed of learning and ultimate performance) of the CM that is being established.
- Once the framework has been established, the training materials to be presented should always be related to that framework. Analysts should understand how hypothesis generation, for example, is related to the production task, the mission

requirement, and the goals of analysis.

- Access to existing CMs: It is important to relate new materials to items that are already in memory. For example, if an analyst has a good background in mathematics and statistics, it is important to insure that the connection is made between the new material to be taught and the relevant background knowledge. In other words, training materials must be developed based on an understanding of the trainee's available CMs and a clear identification of the objectives and the goals of training. The taxonomy of knowledge described in Section 3.3 should be expanded to include individual analysts' existing knowledge bases *and* the required knowledge categories for optimum performance.
- Training and knowledge maintenance must address the problem that analysts have when they change jobs or when they are transferred from one theater of operation to another. The descriptions and attributes of CMs (Section 3.2) suggest ways to make such changes easier for the analyst and more effective for meeting production requirements.
- The views concerning the nature and characteristics of CMs should be considered when developing automated databases as aids to analysis.

9.3 Goal Orientation

The IMTIA cognitive model emphasizes the importance of a context-specific goal orientation in guiding analytic performance. Analysts must know their goals and share goals with other members of the intelligence community to fulfill mission requirements effectively. At the same time, these goals must be explicit for the ideal product to be effective as an evaluation tool. Some research issues are discussed below.

9.3.1 LEARNING GOALS

Analysts should be encouraged to learn how to identify their goals and how to use goals in structuring their tasks and future training requirements. Without goal direction, some analysts may have a great deal of difficulty in determining what is important for them to know at any given time or how to process what they know. One way to increase the likelihood that analysts will learn and aggregate the appropriate data elements in an efficient manner is for them to adopt or be provided with explicit learning goals.

Learning goals might take the form of questions, or they might simply be statements to "learn about X". In addition, the goals could be stated generally (e.g., "learn about the overall threat of enemy forces in Sector X"), or they could refer to specific bits of information (e.g., "learn about the movement of maneuver units in Section X"). The more specific the learning goal, the greater the chance that the analyst will be successful in mastering the goal.

The use of goals in learning complex materials demonstrates that learning goals induce the learner to process the material in such a way that performance on test questions (usually sentence completion items) referring to the goal-relevant material is improved. This improvement cannot be explained solely as a redistribution of processing time. The extent of the improvement is somewhat dependent upon the number of goals to be mastered and the ease with which the learner can locate the appropriate material in a text. With a greater number of goals, most subjects take longer to study the material and they are less likely to learn the information relevant to each goal. If all of the data that are relevant to a particular goal are not located together in the information flow, then it will sometimes be the case that only the information contained in the first reference to the goal-relevant data will be thoroughly studied (Gagne & Rothkopf, 1975). Therefore, there are some limiting factors in adopting learning goals as learning guides, and the limits are dependent upon both the learner and the materials. The available basic research suggests that each analyst should (a) adopt only a limited number of goals to guide performance and (b) acknowledge potential interpretive biases caused by concentrating too heavily on the initial information pertinent to the goals. However, no research exists on learning improvements with multiple goals when those goals are hierarchically organized, as proposed in Section 5.1. It is likely that multiple goals, when hierarchically organized, will enhance learning rather than impede it. This might be a fruitful and interesting area for investigation.

9.3.2 SHARED GOALS

In developing shared conceptual models and in identifying relevant goals, a connection must be made between the goals that are to be shared and goals that are already important to the individual. Individuals have different goals, but to optimize teamwork, there should be some shared goals at some level of the hierarchy. Both during training and in the work setting, it is suggested that the common goals of analysis be made personally important for each analyst.

Shared goals promote the development of SCMs. Though analysts need not accept the users' goals as their own, they do need to know and understand them.

For purposes of training and improvement of analytic performance, it is necessary to identify a hierarchy of goals, subgoals, and tasks and to relate this hierarchy to the cognitive skills required to perform the task.

9.4 Issues Related to Threat

Threat is one of the primary conceptual issues that intelligence analysts deal with. A threat model has been developed by Logicon to serve as a shared conceptual model between analysts and users, and to provide a basis for making more accurate intelligence evaluations and predictions. Much research remains to be done, however, for the purposes of the threat model to become fully realized.

Research related to threat can be divided into two categories:

1. Research related to the *perception* of threat.
2. Research related to the *parameters* of the threat model.

9.4.1 THREAT PERCEPTION

There are several areas with potential payoffs for further research in evaluating and measuring threat perception.

1. The payoffs are in selecting optimum reporting rates for threat information to ensure that the user can react with control. Too frequent reporting may reduce the significance of changes or decrease the user's ability to detect trends. Too infrequent reporting may decrease the user's ability to respond without panic.

   Research in this area would be concerned with ways to measure the user's reaction to threat information as a function of reporting rate.

2. The user's reaction to threat in general involves a decision regarding allocation of resources for control. The impact of uncertainty is to reduce the user's perception of control and increase the probability of errors in battlefield resource allocation.

   Research in this area would be directed at mechanisms to measure the user's level of uncertainty as a means of feedback to the intelligence production operation.

3. Assuming that the Milburn and Watman (1981) model is valid, it would be useful to devise means for an objective evaluation of observable behavioral responses (i.e., sense of comfort, challenge, alienation, panic) associated with perception of threat and control. Research questions would deal with the differences between such observable responses in the strategic and the tactical battlefields. A possible approach would be to review intelligence cases with these factors in mind, namely perception of threat, available physical control, and physical responses associated with different degrees of each. Such a review should attempt to determine if a correlation exists that would validate the Milburn and Watman model.

4. An additional research area concerns the problems of the extraneous factors that affect intelligence analysis and reporting, as discussed above (i.e., national policy, user idiosyncrasies, etc.). While not strictly a problem of intelligence analysis *per se*, it is obviously a source of many poor analytical products.

   The fact that so many extraneous factors impact adversely on the intelligence product is a matter of great concern to observers of and participants in the U. S. intelligence community. The IMTIA studies suggest that these problems are primarily due to a lack of shared conceptual models, shared goals, and to poor communication. The IMTIA cognitive model contains several useful concepts that, if applied, can help alleviate these shortcomings of the intelligence production cycle.

9.4.2 PARAMETERS OF THE THREAT MODEL

As discussed in Chapter 6, the threat model has three major aspects: white, red, and blue. Each of these is made up of numerous elements that have variable impacts on the implications derived from the model. The implications of concern to intelligence analysts are:

- How to assess threat.
- How to assess threat credibility.
- How to communicate threat.

- Analysts' and users' reactions to threat.
- How to evaluate threat.

It is possible that these issues are treated differently by analysts as they view the battlefield from the white, red, or blue perspective, respectively. It might be interesting to investigate this idea.

There would also be a high pay-off value in developing other notions underlying the threat model.

For example, not all elements of the threat model have the same relative importance for the various analytic tasks. Research in this area would consist in identifying the relative importance of the threat model elements for assessing situations, making predictions, or evaluating and dealing with uncertainty.

A better understanding of how uncertainty and risk affect analytic performance and products could make a significant impact on training. For example, some research should be devoted to identifying different *types* of uncertainties, such as uncertainties concerning:

1. Currently existing physical structures (e.g., tanks, enemy installations).
2. Future physical structures (e.g., new weapons).
3. Current non-physical red elements (enemy doctrine).
4. Future non-physical red elements (enemy intentions).
5. Current white elements (given inadequate maps, for example).
6. Future white elements (e.g., weather).
7. Current and future blue elements (e.g., availability of resources).

These uncertainties are categorized by "types". The question is, do the types of uncertainties have differential effects on the tasks. Also, are the types of uncertainties correlated in some way with the judged degrees of uncertainty that a commander might have? That is, are uncertainties treated differentially depending on type? Given certain degrees of uncertainty, how are predictions affected? Specifically, are probabilities assigned differentially?

Other questions related to uncertainty might be asked, such as:

- What is the judged risk, given different types of uncertainties?
- How are the probabilities of events treated, given differential judged risk?
- How do analysts/commanders estimate reliability, validity, or countering capabilities of various types of information?

All these factors should be more carefully evaluated, the literature searched for information on these factors, and a research program designed to answer some of the more important questions.

In summary, the following issues related to the threat model should be investigated:

- The relative importance of the parameters of the threat model as they impact on the prediction of threat.

- The dynamics of the parameters; i.e., which factors change faster than others and how these changes impact on each other.
- The effects of different degrees of uncertainty on decision making (i.e., humans tend to deviate from normative models of decision making: are these deviations a function of the uncertainties associated with the different factors that need to be considered when making decisions?).
- Whether there are different *types* of uncertainty and whether these types have a differential impact on decision making and strategic predictions. For example, are uncertainties related to physical items (e.g., existing enemy installations) treated differently than uncertainties related to hypothesized behavioral items (e.g., future troop movements or enemy intentions)?
- Whether differences in uncertainty types affect how probabilities are assigned, how risk is perceived, and how validities, reliabilities, and countering capabilities are estimated.
- How different degrees of uncertainty affect the product outcome or the reporting of the product.

9.5 The Ideal Product

The concept of the ideal product arose out of the need to define a baseline state for the cognitive model. That is, an assumption was made that one can define an ideal analyst performing ideally and producing an ideal product. This baseline state would serve as the evaluation criterion for actual performances and products. The differences between the ideal and the actual would be used to identify training needs, as well as areas where maintenance of knowledge or skills should be focused. These assumptions should be investigated for their validity and usefulness.

9.6 Conclusion

Several research topics and training issues have been discussed. No specific methods have been proposed for actually performing experiments. In general, however, most issues discussed could be subjected to controlled experiments on the one hand, or could be usefully investigated by combining in-depth interviews of on-the-job intelligence analysts with results from the existing cognitive and analytic literature.

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