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COMPARISON OF EXPERIMENTAL ROTOR DAMPING DATA-REDUCTION TECHNIQUES

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Abstract

The ability of existing data reduction techniques to determine frequency and damping from transient time-history records was evaluated. Analog data records representative of small-scale helicopter aeroelastic stability tests were analyzed. The data records were selected to provide information on the accuracy of reduced frequency and decay coefficients as a function of modal damping level, modal frequency, number of modes present in the time history record, proximity to other modes with different frequencies, steady offset in the time history, and signal-to noise ratio. The study utilized the results from each of the major U.S. helicopter manufacturers, the U.S. Army Aeroflightdynamics Directorate, and NASA Ames Research Center using their inhouse data reduction and analysis techniques. Consequently, the accuracy of different data analysis techniques and the manner in which they were implemented were also evaluated. It was found that modal frequencies can be accurately determined even in the presence of significant random and periodic noise. Identified decay coefficients do, however, show considerable variation, particularly for highly damped modes. The manner in which the data are reduced and the role of the data analyst was shown to be important. Although several different damping determination methods were used, no clear trends were evident for the observed differences between the individual analysis techniques. From this study, it is concluded that the data reduction of modal-damping characteristics from transient time histories results in a range of damping values. This degree of uncertainty should be considered in interpreting experimental data trends, and when performing correlation with analytical predictions.

Notation

$\lvert F(\omega)\rvert$	Fourier transform magnitude at frequency
t	time, sec
ζ	critical damping coefficient (rotating system)
ζ_k	inplane motion measurement signal for kth blade
ζ_{1c}	cosine multiblade inplane measurement
σ	modal decay coefficient, 1/sec
Ω	rotor rotation speed, rad/sec
ω	modal frequency, rad/sec

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Introduction

The ability of the helicopter designer to develop new rotor systems with acceptable aeroelastic stability characteristics is dependent on the use of accurate analyses to predict rotor dynamic behavior. For new bearingless-rotor-system configurations, these analyses have yet to demonstrate an ability to accurately predict rotor stability for configurations that are major departures from the previous designs. To evaluate the accuracy of these prediction methods, carefully obtained experimental data are required to provide a database for correlating and validating these analyses. In other cases, when rotor designs are proposed that go beyond the current analysis capability, experimental programs are sometimes the only means for evaluating the design concept. In light of these considerations, the use of experimental data obtained from model rotor systems is important to the understanding and prediction of rotor system dynamic behavior.

Although numerous experiments have been performed to provide aeroelastic stability data on advanced rotor-system designs and to establish a database for validating analytical prediction methods, little work has been performed to quantify the capability of the experimental process to acquire accurate aeroelastic stability data. A number of factors contribute to the experimental process: design and fabrication of the models; verification of the system's design parameters (stiffnesses, inertias, dampings); model operation; instrumentation and quality of data signals; data acquisition; data reduction and analysis. This entire process must be carefully carried out to ensure the reduced data from the test program adequately establish system stability levels, allow for accurate determination of stability trends with operating condition and parametric variations in the test configuration, and can be used for correlation with analysis.

It is widely recognized that the experimental determination of aeroelastic stability from model and full-scale helicopter rotor dynamic systems is statistical in nature. Even when given the most carefully controlled experiment, the determination of aeroelastic stability characteristics (modal frequency and damping) is not exact. Different data records taken at the same operating conditions typically yield repeatable modal frequencies yet give different modal damping values. Many researchers acknowledge this variability by reporting the results from several different data records, each obtained at the same operating conditions. Such an approach establishes the inherent variability in the data resulting from the entire experimental process (model operation, data acquisition, data reduction, and data analysis). However, such an approach does not provide any indication from where this variation comes. If the sources could be identified, it is possible that appropriate steps could be taken to ensure minimal impact of these factors in the final results.

In addition, this approach also implies that, for each data record being analyzed, there is only one corresponding frequency and damping value. This concept of uniqueness is shown in this study to be incorrect.

This study attempts to evaluate the importance of the data reduction and analysis steps in establishing the variability (or the confidence limits) in rotor aeroelastic stability determinations. This study is limited to the specific applications of data reduction and analysis techniques used within the helicopter technical community. Some of the factors that influence the statistical aspects of experimental stability data are identified and evaluated.

Objectives of Study

This study concentrates exclusively on the techniques currently being used within the rotorcraft community to reduce and analyze small-scale helicopter rotor stability data from transient time histories. The approach used removed the uncertainty associated with the model design and fabrication, the definition of its physical parameters, or its operation since the starting point of this study was analog data records which were taken from various experiments. Each analyst was provided the same information. Consequently, this study considers only the data reduction and analysis steps and their impact on the final, reduced aeroelastic stability parameters. The objectives of the current study are:

1. Evaluate various data reduction techniques used to determine aeroelastic stability characteristics.

2. Determine the importance of the analyst and his techniques in reducing experimental data records.

3. Investigate and attempt to quantify the effects of different test variables on the data reductions and analysis process, including

   a) rotor-system damping level

   b) type of measurement signal analyzed

   c) proximity of other modes to the mode of interest

   d) signal-to-noise levels

4. Establish a degree of confidence in identified stability characteristics for aid in interpreting level of correlation with analytical predictions.

This study was undertaken in support of the Integrated Technology Rotor (ITR) Methodology Assessment program. The results of this study establish a perspective regarding the conclusions of the ITR correlation activity and, in fact, any aeroelastic stability correlation activity. This study also yields a better engineering appreciation of the inherent statistical nature of experimental aeroelastic stability data. In doing so, it establishes the degree of correlation that one can expect from the use of these and similar experimental data when comparing with analytical predictions.

Approach

The approach used in this evaluation of experimental helicopter rotor inplane stability characteristics was to have several organizations, each using their own data reduction and analysis techniques, determine the inplane modal frequency and damping values from 30 experimental data records. The data were provided to each analyst on an FM analog tape (tape speed 7.5 ips; carrier frequency of 13.5 KHz). Data records were between 6 and 15 sec in length. All data records were from resistance-type strain gages installed at the rotor-blade root. Maximum half peak-to-peak voltage was approximately 2 volts for each record. The data time histories were on only one data track, with a second track used as a voice channel to aid in data reduction. The documentation provided with the analog tape identified the location on the tape of each data record, its length, and the approximate modal frequency of interest for analysis.

All of the transient time history data records were acquired in small-scale helicopter rotor tests. Model rotor operation was between 550 and 1100 rpm for the cases selected. The data records were inplane (lead-lag or chordwise) strain-gage measurements. Data were used from soft inplane ($\omega < \Omega$) and stiff inplane ($\omega > \Omega$)

rotor configurations. Single-blade measurements, as well as combined or multiblade measurements, were included in this study. Data from both isolated rotor and rotor/body models were also included in the study. Therefore, the analyst had to analyze modal characteristics from approximately 1 to 23 Hz.

The 30 data records provided each analyst were not identified with any particular rotor system, test configuration, or experiment. No information was provided on the dynamic characteristics of the rotor model used for the data records. The data records were put in random order to further reduce attempts by the analyst to assume information regarding each data record. No information was given on the type of data channel or measurement signal being analyzed. In addition, neither the type of transient excitation used nor the rotor operating condition were specified so the analyst could not a priori eliminate signal components exclusively caused by rotor excitation, rotation effects, or other modes.

The experimental data used were taken from several model helicopter rotor tests reported previously.[1-5] These data sets are listed in Table 1. Three of the data sets included data from rotor configurations used in the ITR Methodology Assessment program.[6] The last two were chosen as representative of a current, advanced bearingless-rotor configuration with a full-scale counterpart (unlike the other three rotors which were designed, in part, to acquire data on idealized rotor hub configurations). The test conditions at which the data were obtained are given in Table 2. These test conditions are considered representative of the data acquired in each test program.

Each data set was chosen for several reasons which are summarized in Table 3. These rotors and the operating conditions allowed the study to consider a range of rotor modal frequencies and damping levels, and signal background noise levels (both random and periodic). The sources of signal contamination shown in Table 3 are other modes (coupled rotor/body configurations versus isolated rotor configurations), random noise superimposed on individual signals in addition to the background noise in the baseline signal (data set 4), and periodic noise due to excitation of the rotor system in forward flight. The use of different signals in data set one was evaluated when time histories for ζ_1, ζ_2 and $(\zeta_1 - \zeta_2)$ were analyzed for the same test condition. Variable frequency refers to evaluating the modal frequency and damping parameters with a variation in the rotor-rotation rate which results in changing modal frequencies. The data acquired near resonant conditions for these systems provided the opportunity to investigate the influence of modal frequency proximity in the time history. Only one data set (number 3) had a mean offset in each analog record of approximately -1 volt. All other data records had steady offsets less than ±0.2 volt.

Analysis

Each organization participating in this study was encouraged to use the data reduction and analysis techniques that would provide their best determination of identified frequency and damping levels from the analog time histories. The techniques used by each organization are listed in Table 4. Only two digital transient time history data analysis techniques were used: the moving block analysis and Prony's method. Although both analyses assume sinusoidal exponential decay of linear, second order systems, the Prony method can specifically account for several degrees of freedom in the time history, each at its own frequency with its level of damping. The moving-block analysis uses the identified modal frequency and then analyzes the decaying time history for the single degree-of-freedom mode at that frequency.

The moving-block analysis technique[7] assumes that the decaying transient time history is a viscous and lightly damped, single degree-of-freedom sinusoidal signal. The modal frequency, ω, is first identified within the decay portion of the record typically using an FFT. Using this frequency, a discrete Fourier transform of the decay signal is calculated using only a portion, or block, of the sample record. This calculation is performed for a number of blocks moving through the decay record with each block having the same number of discrete data points. The natural logarithm of the Fourier coefficient magnitude at the analysis frequency, $|F(\omega)|$ is then plotted versus time where the time is given by the location in the original record where the analyzed block of data begins. This yields

$$\begin{aligned} \text{Slope} &= \ell n|F(\omega)|/dt \\ &= \sigma \\ &= -\zeta\omega \end{aligned}$$

From this definition, the decay coefficient σ is negative and the critical damping coefficient ζ is positive for a stable mode.

It should be noted that, although five organizations used the moving-block analysis, because of the hardware systems and the preferences of the individual analysts, each implementation of the moving-block process was different. These differences in implementation, as well as the role of the analyst in the data analysis process, are the sources of disagreement between the organizations that used the moving-block approach in the resultant identified modal parameters. One objective of this study is to quantify these differences in the final identified frequency and modal decay coefficients.

Bell Helicopter used the Prony method to analyze the transient time histories.[8] This method treats the time history as a sum of complex exponential functions. The roots and coefficients of a difference equation are solved directly for an m-order model from a set of 2*m equations using 2*m discrete data points; approximate coefficients and roots can be determined using more that 2*m data points via the method of least squares. For this study, the model order was chosen to be 20.

A third analysis technique was employed in this study, a nondigital data analysis using a measurement of the time-to-half amplitude from a hard copy of the time history. This hand analysis of the data records is similar to the data analysis approach used prior to 1970 and the advent of digital data analysis for aeroelastic stability determinations.

Further detail on the specific implementation of the data reduction and analysis steps from each participating organization is presented below. One organization used analog prefiltering prior to digitization; no organization utilized digital filtering subsequent to digitization.

<u>U.S. Army Aeroflightdynamics Directorate</u>: The moving-block program analyzed up to 5 sec of data digitized at 100 Hz. A fine resolution of the modal frequency for analysis was determined using Goertzel's algorithm. Typically, the block size was set to approximately one-fourth the edited signal length.

<u>NASA Ames Research Center</u>: The moving-block program analyzed 1024 samples of digitized data. In general, a sampling frequency of 128 Hz and a record length of 8 sec were used. In cases where the transient data record was greater than 8 sec, a sampling frequency of 64 Hz with a 16 sec record length was used.

<u>Hughes Helicopters, Inc.</u>: Approximately 15-sec data records were acquired at a 1000 Hz sampling rate. The modal frequency was determined by choosing an appropriate harmonic number for the Fourier transform, and then slightly varying the edited time segment length. For the moving block, block size was chosen to yield about 50 blocks for the edited time segment, and typically, only every other point within the block was used.

<u>Bell Helicopter Co.</u>: In the Prony method, a maximum of 20 individual modes were used in the analysis to represent the time history. The calculated time history was visually compared to the actual data record for satisfactory agreement. The sampling rate was 256 samples per sec. Typically, only a few seconds of data were analyzed.

<u>Boeing Vertol Co.</u>: Digitized data records were acquired at a sampling rate of 500 Hz. Typically a 4-sec portion of the transient decay record was utilized in the moving block analysis. Usually a one-half block size was used without neglecting any data points within the block.

<u>Sikorsky Aircraft</u>: The data reduction and analysis was performed at the West Palm Beach flight test facility. The analog data were low-pass filtered with a cut-off frequency of 30 Hz. The data were then sampled at 250 Hz. The moving block program allowed for 512 digitized samples. In general, only every other point was used in the analysis.

General Discussion

There are a number of factors which should be considered in interpreting the results of this study. These factors were identified prior to and during the conduct of the program. They are summarized below.

(1) <u>Data records were of varying quality</u>. This is representative of virtually any aeroelastic stability test program. The length of each individual data record was between 6 to 15 sec long. This required selection of various record lengths for data analysis. The level of excitation and modal damping resulted in a range of transient decay time histories from clear, several-second-long exponential decay records to relatively rapid signal reductions to the baseline level. The signal-to-noise levels were different for each record and were, in fact, deliberately increased in several records to evaluate the influence of background noise on the analysis process.

(2) <u>The data records did not explicitly provide information on when forced excitation was terminated</u>. Although the time histories were intended for transient decay analysis, several records did include portions of forced response at the beginning of the time history. The forced response was obtained by either fixed system excitation or with sudden changes in blade pitch. It was left to the data analyst to select that portion representing exponential decay of the data record for analysis. Incorrect selection of a portion of the record (which included forced response) would result in incorrect damping determinations. This could have been overcome by providing the analyst a second data track which

indicated both the nature of the system excitation and when it was terminated. However, each record was carefully chosen to allow for a reasonable portion of the data record to be easily observed as the decaying transient time history portion. Consequently, this should not have impacted the reduced damping determinations when appropriate care was taken.

(3) The analyst had no familiarity with how the data were obtained. This meant that the analyst could not use his familiarity with the rotor model, how the data were acquired, or the anticipated modal characteristics to guide him in his analysis. Consequently, the analyst could rely only on his analysis techniques and experience in obtaining the modal characteristics from these records. To avoid making the modal identification process too difficult, the analyst was provided the approximate modal frequency for the analysis for each data record.

(4) The dynamic system being tested was not a linear single degree-of-freedom system. Like most aeroelastic systems, the models tested could not be fully characterized as a linear system. As such, the transient time history decay records could not be perfectly modeled as a linear system exponential decay over the entire transient record. This is an inherent problem of helicopter aeroelasticity. However, in implementing the data analysis, the analyst must recognize the limitations of the process and obtain the best estimate of the equivalent linear system. This often requires evaluating the data record where the transient amplitudes are likely to have only linear damping characteristics. Likewise the presence of many modes in the data record must be best addressed through the data reduction and analysis process. For this study, each analyst attempted to identify the equivalent linear system frequency and damping characteristics of the fundamental rotor inplane bending mode.

(5) The data record used were not necessarily those analyzed in prior publications documenting that specific test. The first three data sets identified in Table 1 were taken from the data tapes acquired in the experiments used for the ITR Methodology Assessment program. Data sets 1, 2, and 3 correspond to configurations A/4, C/3, and D/1, respectively. During the test programs, numerous data records were acquired at each test condition, and only a portion of those were reduced and analyzed to document the systems behavior. Consequently, the individual data records for data sets 1, 2, and 3 may or may not have been analyzed and are included in the results presented in Refs. 1-3. However, each record that was analyzed as part of this study from data sets 1, 2 and 3 should be considered to be fully representative of these data, and can be used for direct comparison with published results.

In interpreting the results from this study, the variability in the identified damping from one single data record was not accounted for in the published results of Refs. 1-3. Rather, the variability, or scatter, in these references are due exclusively to the range of individually determined damping levels obtained through the analysis of several different time history data records. Each of these tests used the U.S. Army Aeroflightdynamics moving- block analysis described above for data reduction and analysis. The data records used for data sets 4 and 5, in this study were, in fact, those analyzed and reported in Refs. 4 and 5 respectively. The reduced modal damping levels given in Ref. 4 were obtained from hand analysis of strip-chart records. Reference 5 used the Prony method described above.

Results

The results from this study are the determinations of the modal frequencies and damping values of the time history data records. The legends on each frequency and damping figure identify the organization providing this result (see Table 4 for the key). Every organization provided results for each data record except where noted. No identified modal frequency results are presented for the hand analysis NASA(H).

The first results are presented in Figs. 1, 2, and 3 for data set number one, isolated hingeless rotor experiment (Table 1). The operating condition is 1000 rpm. Collective pitch is varied between 0° and 8°. The measurement signals analyzed were obtained by subtracting the inplane bending moment signal of blade 2, ζ_2, from the inplane bending moment signal from blade 1, ζ_1. The identified inplane modal frequency is shown in Fig. 1. Because of the relatively low background noise levels for this two-bladed rotor in hover, frequency determinations are very consistent with less than 2% variation from the mean identified frequency. These small variations are, in part, due to frequency resolution of the particular data reduction technique. The corresponding damping determinations from each analysis is shown in Fig. 2a. For the 4° collective pitch operating condition, only three analyses were able to identify the modal damping level for the mode at 21.4 Hz. There is little scatter in the reduced results. However, variability in the decay coefficient σ of 0.3 to 0.4 sec^{-1} for the records with $\sigma < 0.5$ sec^{-1} exists. For these records, a unique damping value does not exist. In general, there was less variation in the identified damping for the lower damped cases. When the system is slightly stable (collective pitch of 4°) there is virtually no variation in the identified damping. However, when the system is determined to be slightly unstable at a collective pitch of 6°, there is greater variation in the identified decay coefficient. Consequently, the observation that damping can be most accurately determined for lower damped systems does not apply for small negatively damped systems.

Comparing the results of this study with those of Ref. 1 (in Fig. 2b) show the same trend with increasing collective pitch. The thin band shows the range of all the identified decay coefficients for that data record; the heavy band is obtained by neglecting the smallest and largest identified decay coefficient. Eliminating the extreme values results in a significant reduction in the scatter of the reduced data, particularly for highly damped conditions. However, this is not justifiable given that each analysis is indeed correct. It is important to note that, for this data set as well as for the others in this study, it is not possible a priori to identify which analysis will yield an extreme value. Neglecting the largest and smallest values is an attempt to reduce the scatter from the decay coefficient values identified in this study, and to provide smaller ranges of estimates of the decay coefficient for comparison with published results. Also shown in Fig. 2b are the identified decay coefficients AA which represent a second attempt at evaluating damping with the same data reduction technique used in Ref. 1. The data analyzed in this study were not necessarily those actually analyzed and reported in Ref. 1, and yet should be considered to be representative. The AA results from this study agree very well with the previously published results. From these comparisons, damping determinations in this study are generally greater than those published, except at 8° collective pitch. Data scatter is representative of the range of published data. In this study, the inplane mode was found to be stable at 4° collective pitch unlike Ref. 1.

Data set number one, which has been studied in Figs. 1 and 2, is from a stiff-inplane, two-bladed rotor with a dimensionless lead-lag frequency approximately 1.5 times the rotor rotation rate. Although the data presented in Figs. 1 and 2 used a signal which was obtained by subtracting the inplane motion of the second blade from the motion of the first blade ($\zeta_1 - \zeta_2$) to provide accurate isolated blade behavior, this study also evaluated the use of the individual inplane motions of each blade (ζ_1 and ζ_2) for comparison to determine sensitivity to the measurement signal. The results of this comparison for one data point is shown in Fig. 3. This comparison is for the operating condition shown in Figs. 1 and 2 at a 2° collective pitch and 1000 rpm. The scale of the vertical axis is expanded from that in Fig. 2 to show more detail. From these results, it is noted that less scatter is obtained when using the inplane motion measurement from a single blade then for the ($\zeta_1 - \zeta_2$) measurement. The results also indicate that the signal quality from blade number 2 was perhaps better than that from blade number one. It is not surprising then that a signal composed by combining the two signals results in a signal yielding at least as much scatter as the poorest quality signal. In this case, the variation in the identified decay coefficient from the combined signal is approximately 100% greater than that using the number one blade measurement directly.

The results for data set number two are shown in Figs. 4 and 5. This data set is for a coupled hingeless rotor/body system with the rotor operating at 9° collective pitch. The measurement signal is the multiblade coordinate signal ζ_{1c} which is obtained by appropriately combining the inplane measurement signal from each of the three rotor blades. Figure 4 shows the identified modal frequency from the time history record. This data set has very low modal frequency values ($\omega/2\pi < 6$ Hz), significantly different than the modal frequency values of data set number one ($\omega/2\pi > 21$ Hz). The ability to determine the modal frequency as a function of rotor rotation rate is satisfactory. The greatest scatter is at the lowest modal frequency.

Figure 5a shows the variability in the identified decay coefficient for the results from this study. Again, the higher damped conditions show greater scatter. This is evident from a comparison of 550 rpm (0.7 sec^{-1} scatter) and 900 rpm (1.5 sec^{-1} scatter) operation. The reason for the data scatter at 600 rpm is due to one single high damping estimate. The identified decay coefficient at 600 rpm without this one high value would be more reasonable since it would then be comparable to the data scatter at 650 and 700 rpm (which has the same level of damping). Similar to the results from data set one, the scatter for small, negatively damped decay coefficients is relatively large. From this data set, for the majority of data records, a unique, single value for the decay coefficient cannot be determined. This characteristic is present in all the data sets. The results of this study are compared with published results in Fig. 5b. Once again, the heavy band shows the range of identified decay coefficients with the smallest and largest estimates neglected. Only for operation at 600 and 900 rpm do the decay coefficient extreme values significantly increase the data scatter. In general, highly damped cases show significantly more scatter than the published results. Yet, for all conditions where the decay coefficient is

$\geq -1.0\ sec^{-1}$ good correlation is shown, except for operation at 650 rpm. Here, the results of this study, although showing very little variation between each analysis, are less damped than are the published results. The results AA are also plotted on the figure which represent a second analysis of the data from this test using the same data reduction technique as that used in Ref. 2. The AA analysis is consistent with the other analyses of this study, and significantly deviate from the published results only at 650 rpm.

The results for data set number three are shown in Figs. 6 and 7. The three-bladed rotor is operating at 1100 rpm in hover and collective pitch is varied from -4° to +4°. For this data set the measurement signal is the inplane bending moment of one blade. Since these results are also for an isolated inplane rotor blade model, the variability in the reduced modal parameters for this data set are somewhat similar to those obtained from data set one. As seen from Fig. 6 there is very little discrepancy in the identified modal frequencies between each separate analysis. Even when differences exist, the variability is only about 2% of the mean value. The identified modal decay coefficients (Fig. 7a) show scatter, again, particularly for the highest damped operating conditions. Note the extreme variation at -4° collective pitch. This degree of variability is easily the largest from this study, and occurs for the highest damped operating condition used. It is a bit surprising that the variability is relatively small for -2° collective pitch, yet this is not unlike the results from data set number two.

The results of this study are compared with published results in Fig. 7b. Again, the thin band shows the range of all the identified decay coefficients for that data record, and the heavy band is obtained by neglecting the smallest and largest identified decay coefficient. Also shown are the AA results which again represent a second analysis of the data record (using the same analysis technique as in Ref. 3). Except for the larger amount of variability of the identified damping from this study, the correlation with the published results is good. The trend with increasing collective pitch is obtained. For each operating condition, the extreme identified decay coefficients do increase the range of identified values. Basically, the results from this study would seem to indicate a greater degree of scatter than that given from Ref. 3 for numerous, repeated stability, data records. The agreement between AA and the published results of Ref. 3 is very good.

The results for data set four are shown in Figs. 8, 9, and 10. This data set is for a one-fifth scale model of the Model 680 bearingless rotor system with representative body degrees of freedom. Data records for constant thrust operation (222 N) in hover were analyzed and the identified frequencies are shown in Fig. 8. These results are completely consistent with the frequency determinations of each of the previous data sets. The modal decay coefficients shown in Fig. 9a, however, show somewhat more scatter than do the previous three. If the one single high decay determination for 780 rpm is excluded, the amount of variability in the identified damping for operation at 700, 780, 850, and 950 rpm is almost constant. For this data set, very low damping values ($\sigma > -0.5\ sec^{-1}$) still, surprisingly, yield considerable scatter unlike the previous three data sets. This may be due to the overall quality of the analog data records obtained during this experiment. Figure 9b shows the correlation between this study and the published results of Ref. 4. These results were obtained using hand analysis of hard copy records. In general, reasonable correlation is obtained although the higher damped operating conditions seem to have their damping underestimated in Ref. 4, and the extreme identified damping values significantly increase data scatter at 780 and 950 rpm. Figure 9c shows the comparison of hand analyzed results[4] with the digitally reduced values using the Prony method (BELL) from the same organization, and the hand analyzed results from this study. It is clear that, although the general trends are the same, the use of the two different analysis techniques can result in different identified damping levels. This is consistent with the results of this study. Also, the good agreement (except at 850 rpm) between the two hand analyses indicate less variability between non-digital techniques than between digital techniques.

An investigation of the influence of signal-to-noise ratio was done in this study by superimposing random noise on the baseline time history record of data set four for 850-rpm rotor operation. For this study, the baseline data record was analyzed, then records with first 0.1 volt RMS noise, and then with 0.2 volt RMS noise superimposed on the original baseline data record were analyzed. In both instances, the RMS noise had 0.1 to 50 Hz frequency content. The three time history data records are shown in Fig. 10 with each record's frequency spectra. The vertical scales of the time history plots (Fig. 10a) are arbitrary. The inplane modal frequency was approximately 10 Hz for this operating condition. The 0.2 volt RMS noise masks much of the transient decay record. The noise reduces the transient time history decay noticeably, yet the digital data analysis techniques easily extracted the proper frequency information (not shown). The identified decay coefficient results shown in Fig. 11, on the other hand, show considerable variability which significantly increases with greater noise level. A five-fold increase in data scatter owing to the introduction of the broadband noise is noted for the 0.2 volt RMS noise case. This noise level has virtually no affect on four of the data analyses, including the nondigital analysis and the analysis where the analog data were low pass filtered below 30 Hz prior to digitization. (It is not understood why the BELL or HHI analysis showed particular sensitivity to the noise level.) These results are sufficient to demonstrate the sensitivity of the data reduction and analysis programs to background noise levels.

The results for data set number five are presented in Figs. 12 and 13. Data set number five is for the same fifth-scale Model 680 system used in data set number four, however, the transient time histories were acquired for forward flight operating conditions at 750 rpm. This results in significant periodic noise (1P frequency spectra amplitude up to three times the modal frequency amplitude) present at the rotor rotation rate (12.5 Hz) in the data record which do not decay with the transient fundamental inplane mode motion. Again, the measurement signal is for the inplane motion of one blade. The ability to determine modal frequency is evaluated in Fig. 12. Although the hover condition shows significant scatter (poor quality data record), the inplane frequencies were easily determined with little variability for forward flight.

The identified decay coefficient from this study are shown in Fig. 13a. Except for the exceptionally large data scatter in hover (perhaps owing to poor excitation of the rotor inplane motion which also resulted in poor modal frequency determination), the variability in the damping is somewhat greater than that obtained in the hover results of Fig. 9. The variability itself does not seem to increase with forward speed. The hand analysis results are, once again, as accurate as the digital data analysis techniques, even for forward flight. This is a general observation from each data set. However, it should be noted the use of digital analysis techniques has the advantage of accurate modal frequency determination, a consistent step-by-step procedure for analysis of various data records, and is anticipated to have less dependence on the experience level of the analyst.

In Fig. 13b comparison with the results presented in Ref. 5 are made w th the results in the present study (again, the range of identified values with the extreme data points removed is the heavy band). In general, the correlation is good, except this study would seem to indicate the rotor system is slightly less damped. The same trends with forward flight were observed in this study as in Ref. 5. Lastly, an interesting comparison is made in Fig. 13b between the results of this study and those taken from Ref. 5. Since the data reduction process in Ref. 5 used the same identical data record as was used in this study, it is interesting to compare the published results with this study using the values obtained with the same Prony method for data reduction. Here the differences would be related to the manner in which the two analysts (using the same digital analysis) performed the data reduction and analysis steps. Although for each set of results, the same gross trends are obtained with operating condition, the results of this study show a much greater degree of stability in hover, and do not show a stabilizing effect at high advance ratio. It is clear that the role of the analyst is important in determining the reduced damping parameters, even when identical data reduction techniques are employed.

Conclusions

This study has attempted to quantify the degree of variability in analyzing transient time history data records. The inherent variability in this analysis process establishes a guideline for the degree of correlation one can expect in comparing analytical predictions with experimental data. For a single data record there is no one correct decay coefficient. Although modal frequency can often be established for good signal-to-noise data records, identified modal damping values are inherently statistical and nonunique. The specific conclusions from this study are:

1. Identified modal frequencies showed very little variation except for poor quality data records.

2. Identified decay coefficients do show considerable variation, particularly for highly damped modes with the decay coefficient magnitude greater than 1.0 sec^{-1}.

3. Variability in the identified decay coefficients is dependent on the damping level:
   a) Lightly damped modes ($\sigma > -0.5$ sec^{-1}) have approximately 20% scatter band (±10%).
   b) Heavily damped modes can have greater than 50% scatter band (±25%).

4. No clear trends were evident for observed differences between the individual techniques.

5. The quality or signal-to-noise level of the data record is critical to accurate determination of the modal decay coefficient.

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Reference

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Table 1 Data set identification used in study

Data Set Number (Ref. no.)	Rotor Config.	ITR Config.	Body Modes	Number of Blades	Measurement Signal
1	Hingeless Rotor	A4	No	2	$\zeta_1 - \zeta_2$, ζ_1, ζ_2
2	Hingeless Rotor	C3	Yes	3	ζ_{1c}
3	Bearingless Rotor	D1	No	3	ζ_1
4	Bearingless Rotor	--	Yes	4	ζ_1
5	Bearingless Rotor	--	Yes	4	ζ_1

Table 2 Test conditions for each data set in study

Data Set Number	Rotor Config.	RPM	Collective Pitch, deg	Advance Ratio	Shaft Angle, deg
1	Hingeless Rotor	1000	0 2* 4 6 8	0	0
2	Hingeless Rotor	550 660 650 700 770 810 850 900	9	0	0
3	Bearingless Rotor	1100	-4 -2 0 4	0	0
4	Bearingless Rotor	650 700 780 850** 950	Set to provide 222 N lift	0	0
5	Bearingless Rotor	750	Set to provide 222 N lift	0 .05 .15 .24	0 -1 -3 -5

* Three different signal used.
** Two different levels of superimposed noise used.

Table 3 Summary of characteristics of each data set

Data Set	Signal Contamination			Different Signals	Freq. Variable
	Other Modes	Random Noise	Periodic Noise		
1	No	No	No	Yes	No
2	Yes	No	No	No	Yes
3	No	No	No	No	No
4	Yes	Yes	No	No	Yes
5	Yes	No	Yes	No	No

Table 4 Summary of analysis techniques used

Organization	ID	Type of Analysis
U.S. Army Aeroflightdynamics Directorate	AA	Moving Block
NASA Ames Research Center	NASA(MB) NASA(H)	Moving Block Hand Analysis
Hughes Helicopters, Inc.	HHI	Moving Block
Bell Helicopter Company	BELL	Prony Method
Boeing Vertol	BV	Moving Block
Sikorsky Aircraft	SA	Moving Block

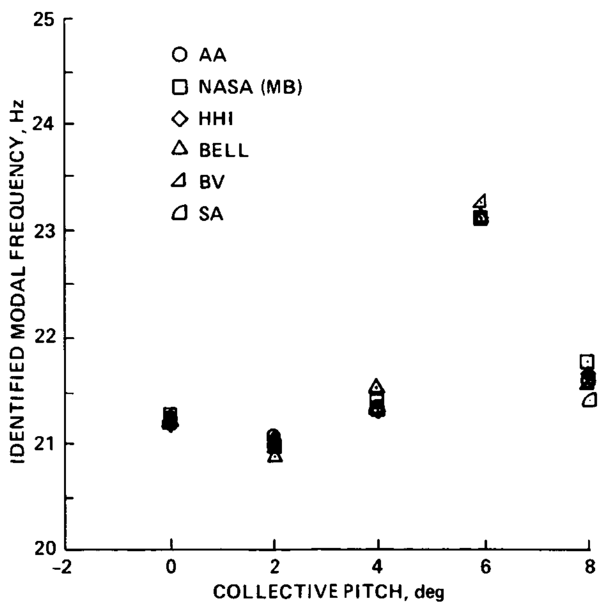
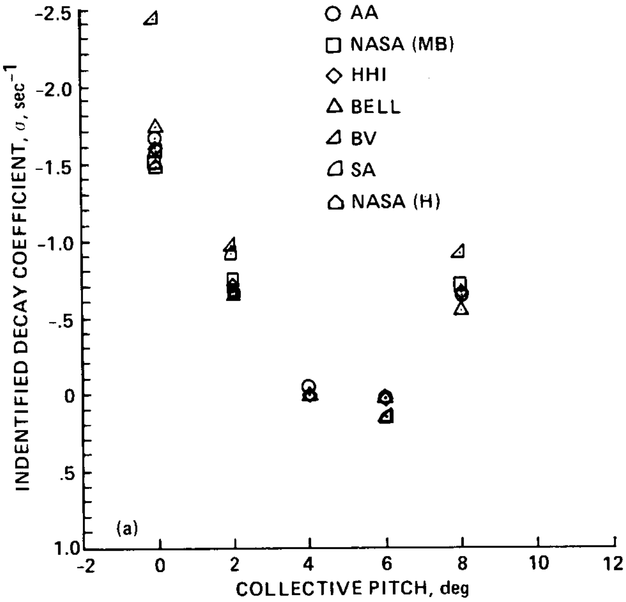
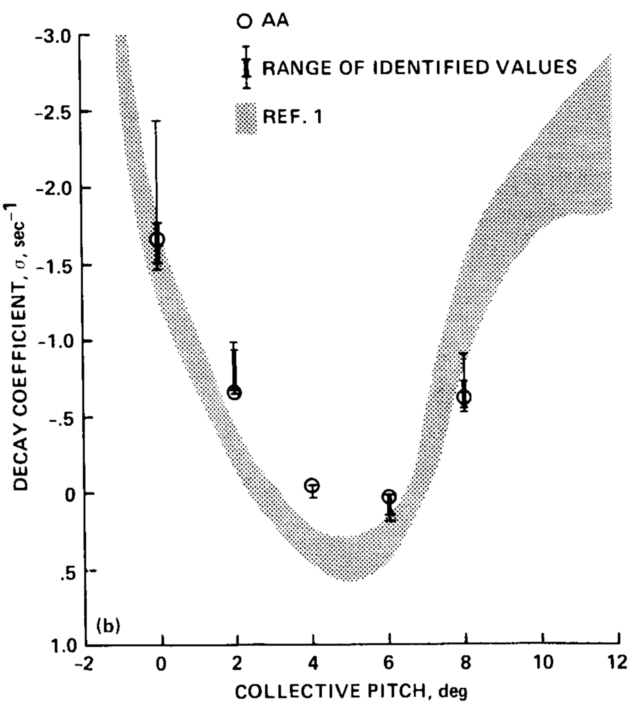


Fig. 1 Identified modal frequency for data set number one; 1000 rpm.



a) Identified modal decay coefficient



b) Comparison with published results

Fig. 2 Modal damping for data set number one; 1000 rpm.

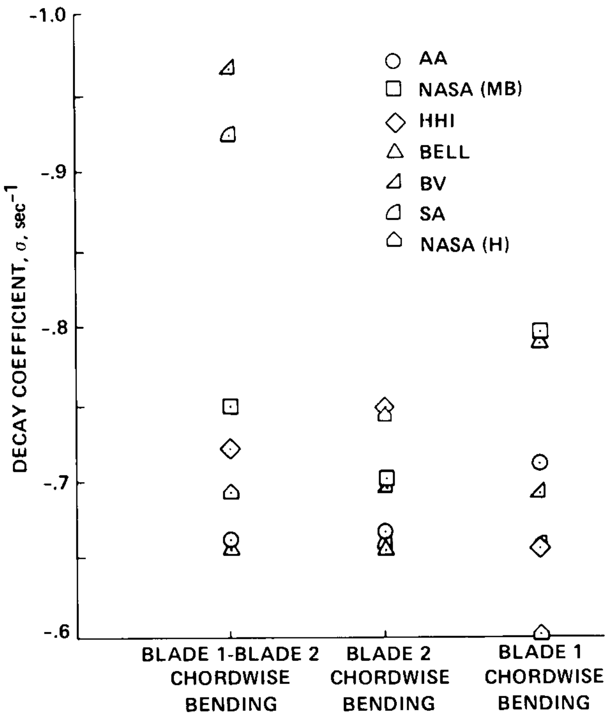


Fig. 3 Comparison between different measurement signals: Data set number one; 1000 rpm, 2° collective pitch.

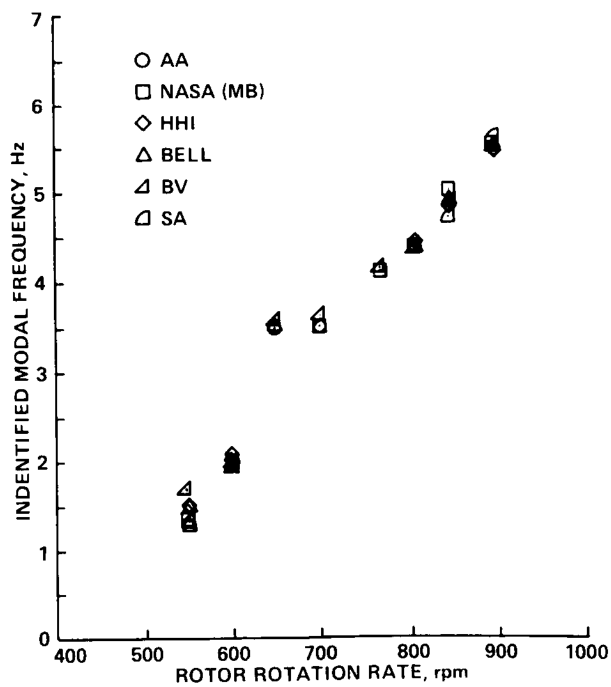
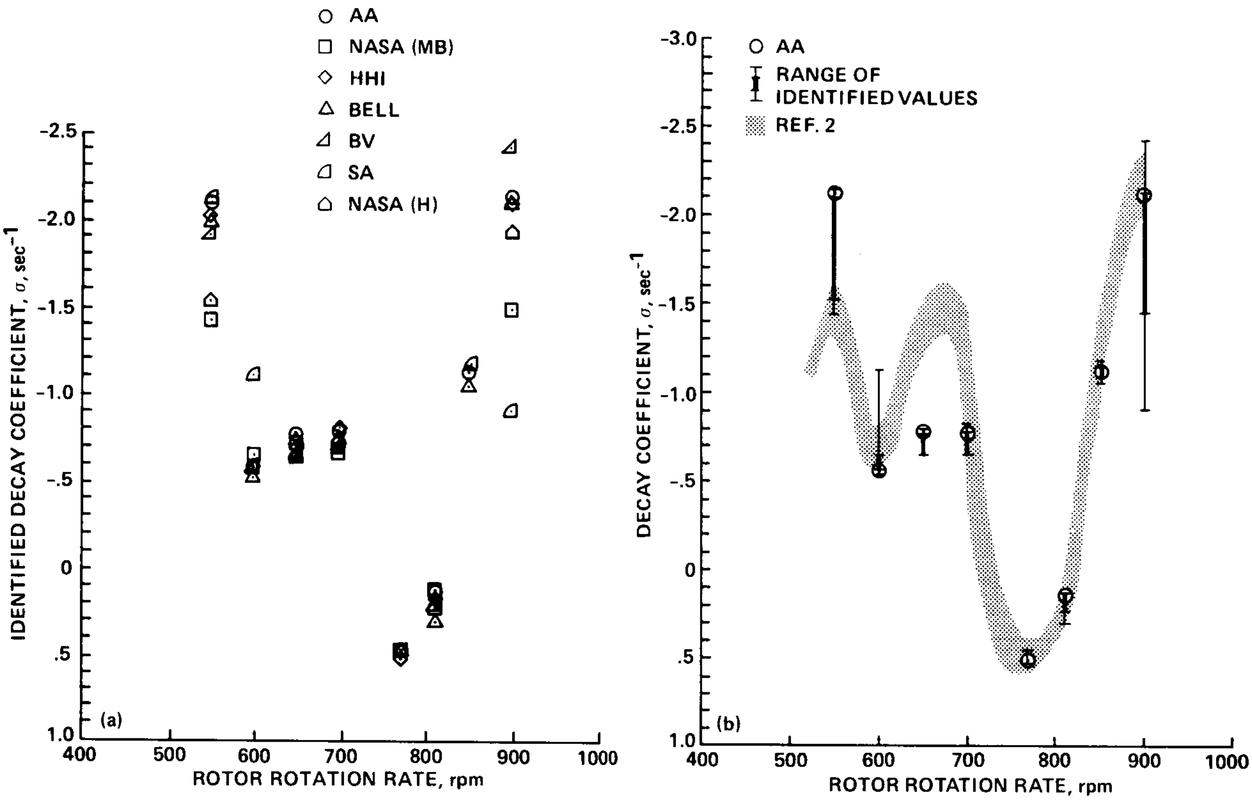


Fig. 4 Identified modal frequency for data set number two; 9° collective pitch.



a) Identified modal decay coefficient.

b) Comparison with published results.

Fig. 5 Modal damping for data set number two; 9° collective pitch.

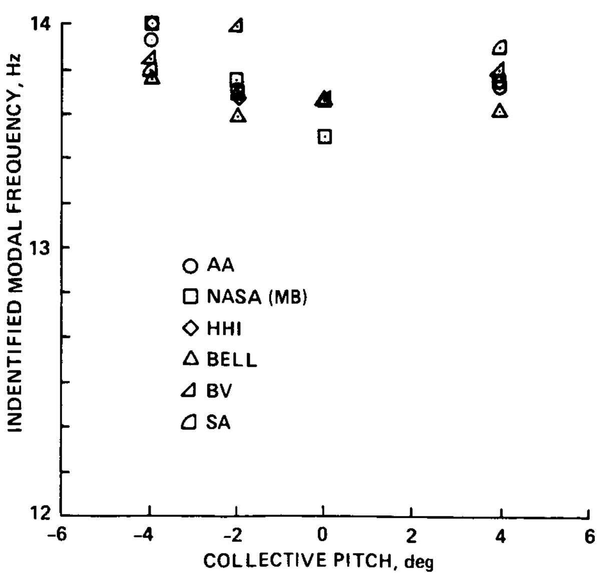
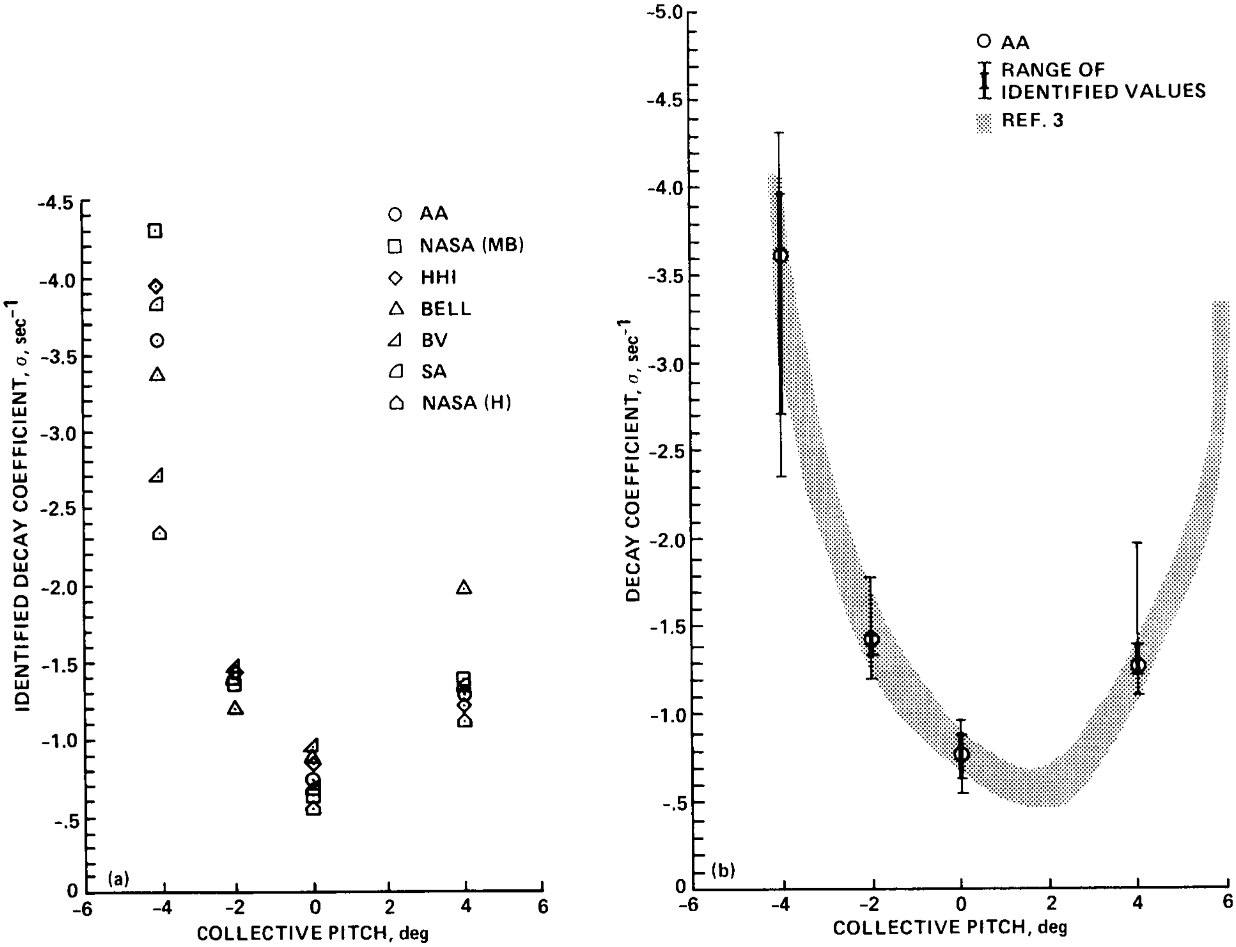


Fig. 6 Identified modal frequency for data set number three; 1100 rpm.



a) Identified modal decay coefficient

b) Comparison with published results

Fig. 7 Modal damping for data set number three; 1100 rpm.

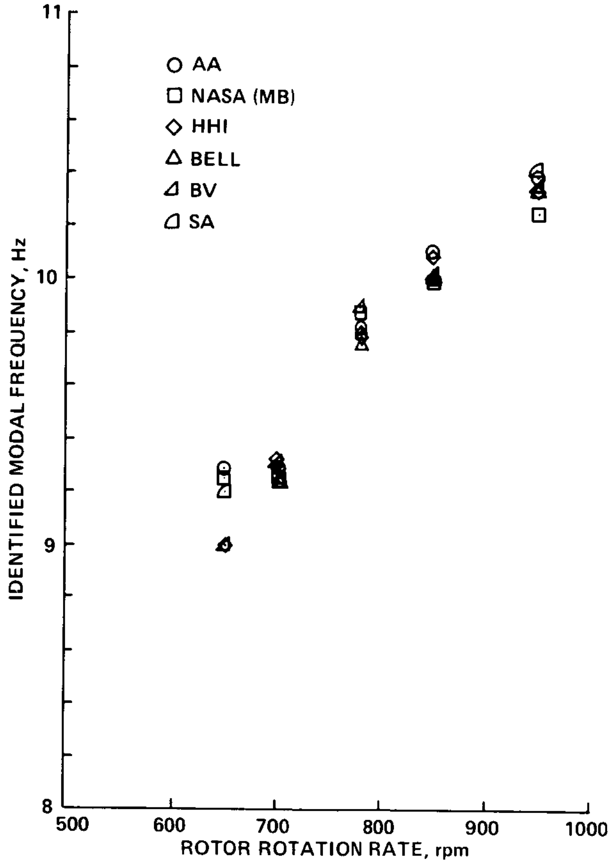
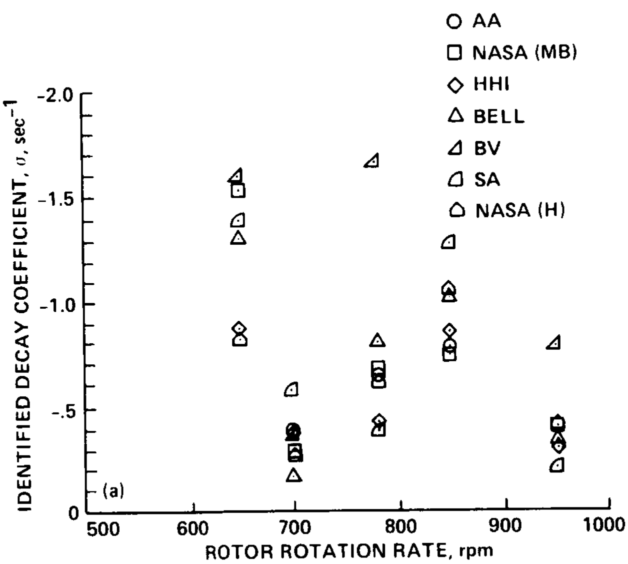
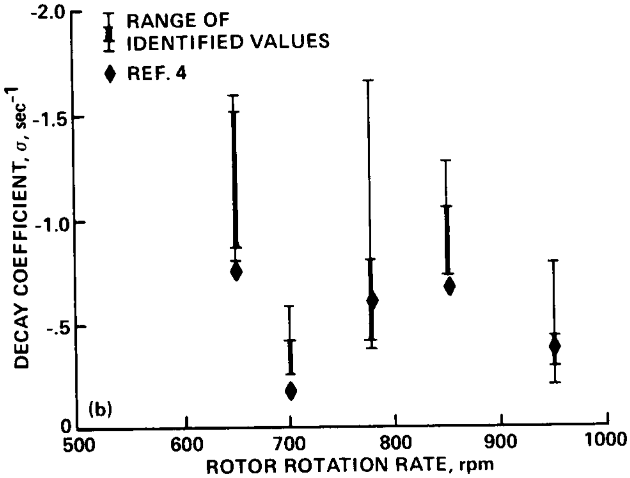


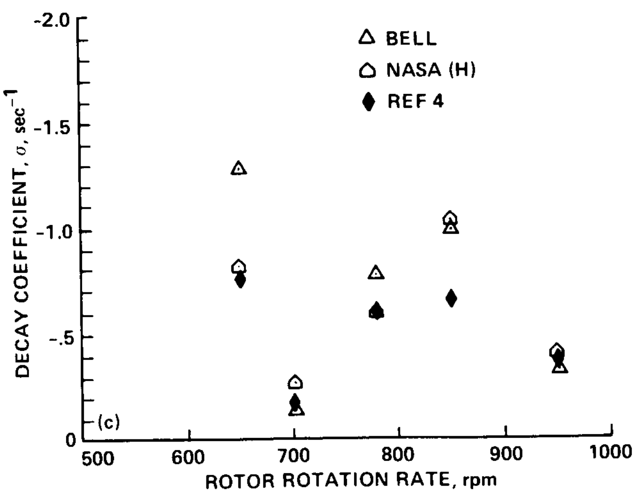
Fig. 8 Modal frequency for data set number four; 222 N lift, hover.



a) Identified modal decay coefficient.

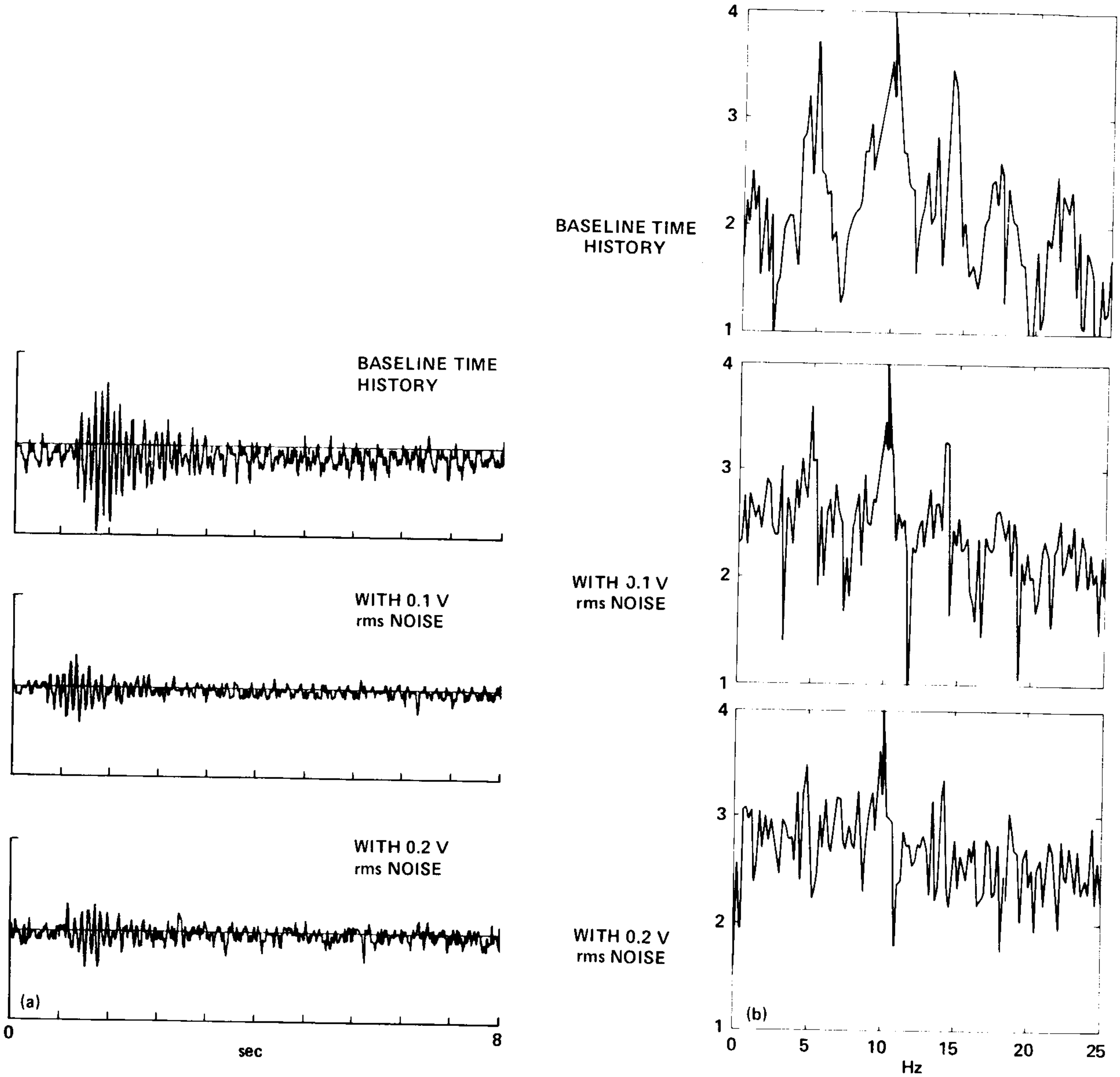


b) Comparison with published results.



c) Comparison with specific analyses.

Fig. 9 Modal damping for data set number four; 222 N lift, hover.



a) Time history records.

b) Frequency spectra.

Fig. 10 Data records with superimposed random noise; 0.1 to 50 Hz, data set number four, 850 rpm, 222 N lift.

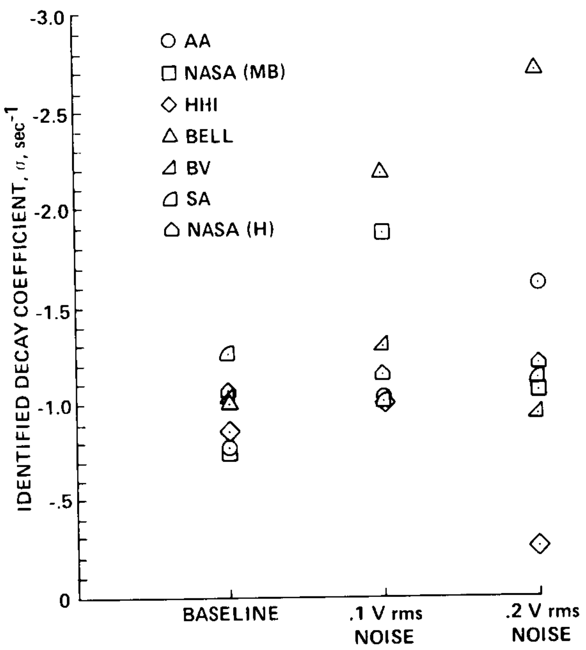


Fig. 11 Influence of background noise on modal damping: data set four.

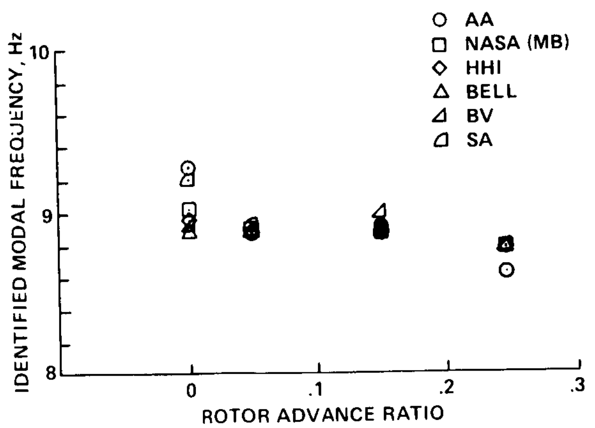
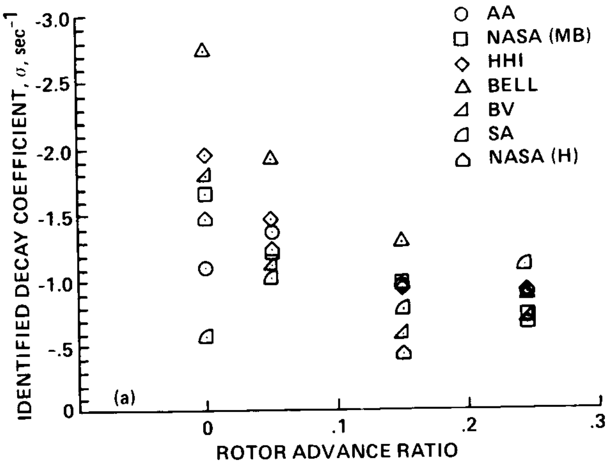
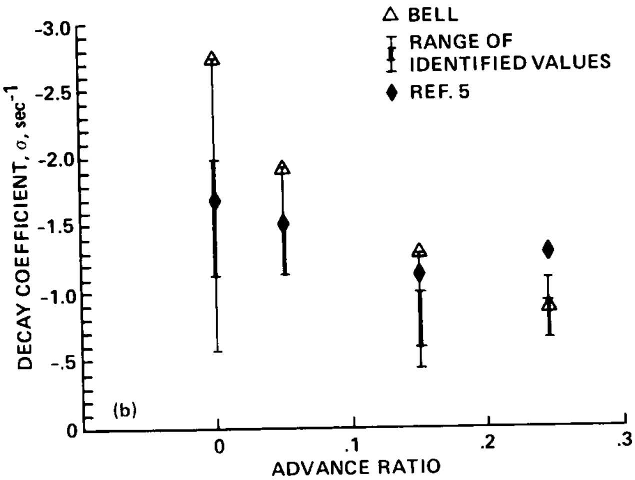


Fig. 12 Identified modal frequency for data set number five; 750 rpm, 222 N lift.



a) Identified modal decay coefficient



b) Comparison with published results

Fig. 13 Modal damping for data set number five; 750 rpm, 222 N lift.