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# Integration Time Required to Extract Accurate Data from Transonic Wind-Tunnel Tests

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**Because the forces and pressures on wind-tunnel models tested at transonic speeds are not steady, even for static aerodynamic tests, integration time is required to obtain data of acceptable accuracy. The integration time required for both static and dynamic tests is evaluated analytically and confirmed by experimental measurements. It is shown that, for static and dynamic tests, the accuracy obtained is a function of integration time, frequency of the signal, and the ratio of the dynamic amplitude to the full signal of interest. In addition, for the dynamic case, the frequency bandwidth used in analysis is important. Results of this study indicate that, for typical data accuracy desired from models in a large transonic wind tunnel (11- by 11-ft), up to the following integration times are required: static force and moment tests, 0.5 s; static pressure tests, 1 s; flutter tests, 30 to 60 s; and random-dynamic tests, 10 s.**

## Introduction

RECENT interest in conducting transonic wind-tunnel tests in facilities with short run times has focused attention on the run time required to obtain accurate data during both static and dynamic tests. Because the forces and pressures on wind-tunnel models tested at transonic speeds are not steady, even for "static" aerodynamic tests, integration time is required to obtain data of acceptable accuracy.

Evidence of the existence of large amounts of flow unsteadiness on models in wind tunnels as well as on aircraft in flight is given in Refs. 1-4. Thus, large pressure fluctuations and, consequently, large force fluctuations can be induced by model geometry and are not due solely to the quality of the flow in the wind tunnel. Furthermore, this unsteady flow on the model, which results from such things as the attached turbulent boundary layer, oscillating shock waves, separated flows, and local vortices, contains a large amount of power over a large frequency range extending to very low frequencies. The significance of unsteadiness at low frequencies is shown later.

The problem of measuring static and dynamic forces and pressure to specified statistical error and confidence limits is directly associated with the analysis time available for averaging or integrating the data. It is generally well understood that the dynamic aspects of the data dictate the integration time requirements. In other words, investigations that are free of dynamics would require very little run time per data point beyond the time required for flow stabilization, and a single instantaneous sample would provide adequate accuracy. However, since some dynamic components are always present, such a sample could contain large errors. It is not unusual for the peak-to-peak variation of the dynamic component of what many people consider as "static" data to be 50% of the true mean. Thus, the error could be ±25%.

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Note that because of the broadband random nature of the unsteady forces or pressures, high-speed instrumentation does not help this problem. Indeed, in itself, such instrumentation emphasizes the problem by reducing the integration time inherent in the instrumentation.

Figure 1 shows schematically why integration time is required for static test data. This figure shows the actual time history of the wing root bending moment on a model of the TACT airplane at $M=0.8$ and $\alpha=16$ deg, while mounted in the Ames 11- by 11-Ft Transonic Wind Tunnel. Note that a single sample could be in error by more than 25% of the true mean and that the dynamic characteristics vary significantly with time. Figure 1 also shows the envelope of the indicated mean as a function of integration time. A similar situation exists for dynamic data.

Determining the integration time required for specified data accuracy in wind-tunnel testing has been a problem for a long time. For static data, this problem has generally been solved by using some form of analog or digital low-pass filtering or integration. Because each facility typically uses a different approach to solve this problem, the integration time used is usually determined for each facility by some type of test. Virtually no information on the results of these tests are available in the literature. A broad discussion of run-time requirements is contained in Ref. 5 and the references therein; however, very little quantitative data are shown to validate the conclusions reached. Because of the information available, a detailed experimental and analytical study was performed to quantify the integration time required to obtain both static and dynamic data of a specified accuracy in the Ames 11- by 11-Ft Transonic Wind Tunnel. It is believed that these results are typical of other large transonic wind tunnels.

## Classes of Aerodynamic Tests

To evaluate integration time requirements, classes of aerodynamic test that require different analysis procedures

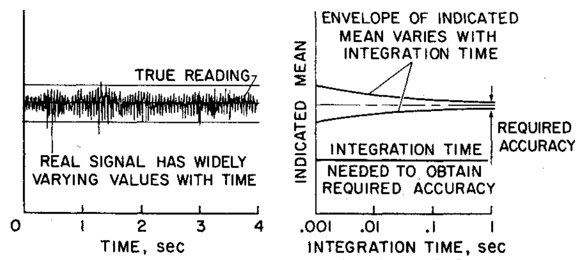

**Fig. 1 Why integration time is needed.**

and consequently different integration times were considered. The major classification distinction is between static (steady-state) and dynamic investigations. Static investigations usually involve force or pressure data, and the analyzed data are intended to represent mean values. For dynamic investigations, different forms of analysis are required that are suitable for the types of waveforms expected from each major class of tests (dynamic stability, self-excited dynamic problems, and stochastic dynamic problems).

## Static Tests

As previously mentioned, local transonic flows can be highly turbulent, causing significant dynamic forces or pressures on an aircraft or model. Typical local loads that cause model force and pressure measurements to have higher dynamic content at transonic speeds than usually experienced at other speeds are shown in Fig. 2. These data were recorded on the wing of an F-111A model at $M = 0.85$ and $\alpha = 6.13$ deg. The sketches show the major regions of flow unsteadiness (shock oscillations and separated flow) that occur on the wing and corresponding typical time histories. Both the steady-state and dynamic distributions of the static-pressure coefficient are shown. Note that the rms value of the dynamic signal can exceed 10% of the mean pressure in the regions of the shock wave or separated flow. Peak-to-peak deviations about the mean can be from 4 to 6 times the rms value.

Figure 3 illustrates the problem of obtaining an accurate estimate of the mean value from a force or pressure time history that contains a significant dynamic component. It is obvious that instantaneous or short-duration samples taken from the time history probably will not be at the mean value. Some form of averaging or integration is thus required to obtain an accurate estimate of the mean. This can be accomplished by lowpass analog filters or by true integration by either analog or digital computers. In any case, either the filter time constant or the integration times required to yield a mean value within a specified error result in about the same run-time requirements. The accuracy of the mean-value measurement depends on the filter time constant or integration time, the frequency content of the signal, and the ratio of the dynamic amplitude to the calibrated full-scale gage sensitivity.

To evaluate the integration times required to extract mean values, the problem has been treated both analytically and experimentally. Assumption of waveform and frequency content are required for the analytical solution. Therefore, the analytical results are only approximations of real-data analysis-time requirements. Typical experimental results that represent actual force and pressure data for several test conditions are also presented.

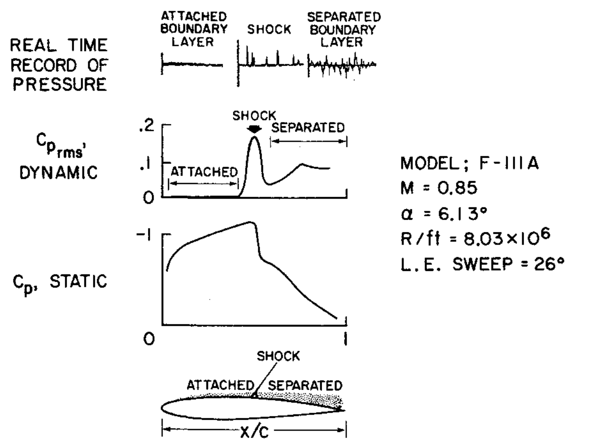


**Fig. 2 Local transonic pressures that result in combined steady-state and dynamic forces and loads.**

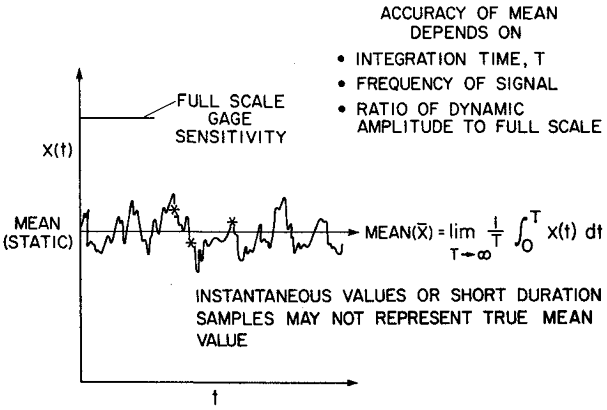


**Fig. 3 Evaluation of mean value.**

### Analytical Prediction of Error

Details of the analytical steady, which is based on the well established principles of statistics and random variables,[6] are contained in Ref. 7. Results of the analysis are shown in Fig. 4, which illustrates the possible error of the estimated mean value as a function of integration time of data assumed to contain white noise within three different frequency bands. These curves show the error for a 95% confidence level and for a constant ratio of the rms value of the dynamic part of the signal to gage full scale of 0.1. The lower cutoff frequencies ($F_L$) are set at 1, 10, and 20 Hz while the upper cutoff frequency ($F_U$) remains constant at 100 Hz. The integration time required for a specified accuracy increases very rapidly as the lower cutoff frequency is reduced. For example, for an error in mean value of approximately 0.5%, the required integration time increases from almost 0.2 s for $F_L = 20$ Hz to approximately 0.75 s for $F_L = 1.0$ Hz. For a given frequency range, error increases directly with the ratio of the dynamic signal to full scale. Note that the error decreases rapidly with increasing integration time up to the time approximately equal to the period of the lowest frequency present, after which the error decreases less rapidly.

### Experimental Evaluation—Force Test

Figure 5 shows an example of the relative steady and unsteady signal content from a typical strain-gage balance recorded during a transonic test of a fighter airplane. The measured mean force and peak-to-peak value of the unsteady portion of the force are shown as a function of angle of attack for a forward normal force and an axial force gage. For the normal-force gage, the peak value of the unsteady part of the force signal is more than 3% of the mean reading over almost all the test range. Thus a single instantaneous reading could differ from the mean normal force by more than 3%. Depending on the location of the moment center and the

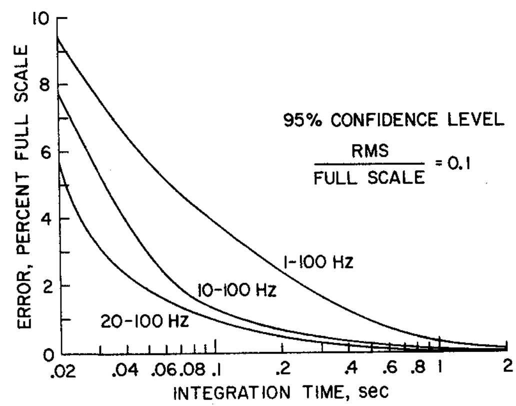


**Fig. 4 Computed error in mean (static) value with superimposed band-limited white noise.**

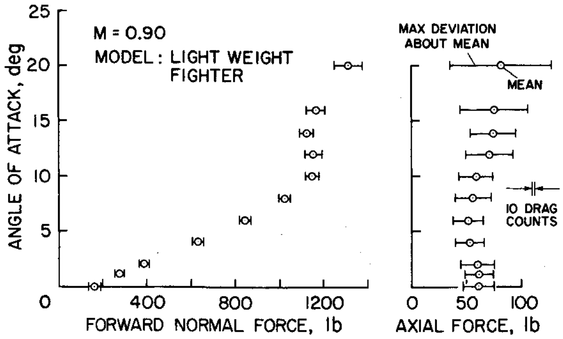


**Fig. 5 Mean and dynamic normal and axial forces on an airplane model**

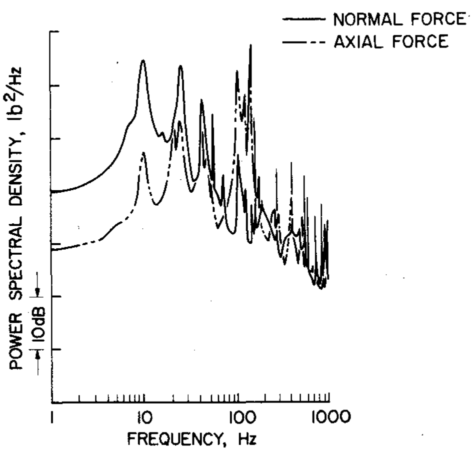


**Fig. 6 Typical power spectra of the unsteady forces measured by a strain-gage balance.**

phasing of the unsteady portion of the force, the corresponding difference in pitching moment could be near 6%.

A much larger effect is shown on the axial force. The peak value is shown to vary from approximately 20% of the mean reading at low angles of attack to 45% of the mean reading at high angles of attack. Thus instantaneous measurements could be in error by about $\pm 20$ to $\pm 50$ drag counts. For conditions near a maximum lift/drag ratio, a drag change of 1 to 2 drag counts ($\Delta C_D = 0.0001$ to $0.0002$) is considered significant for range and payload calculations. For example, an increase of 1 drag count will decrease the payload by approximately 1% for the long-range mission of a large transport aircraft such as the C-5A. Thus, instantaneous readings would produce totally unacceptable errors if used to record what are traditionally considered to be static test data.

Figure 6 is a power spectral density plot of the unsteady component of the force signal for one of the data points discussed in Fig. 5. These data, typical for a model and balance sized for the Ames 11- by 11-Ft Transonic Wind Tunnel, show that the major balance resonances are concentrated in the frequency range of 7 to 200 Hz. In a smaller wind tunnel or one operating at higher dynamic pressure, the balance system will have higher resonant frequencies. However, for high dynamic pressure, the resonant frequency will increase relatively slowly because resonant frequency is a square-root function of stiffness. Thus, the range of lower cutoff frequencies investigated in Fig. 4 is valid for a variety of test conditions in large transonic wind tunnels.

The problem of accurately determining the mean values of wind-tunnel balance signals that contain significant dynamic components is generally recognized, but it is not widely publicized and is easily overlooked, particularly by those unfamiliar with the unsteady flows encountered at transonic

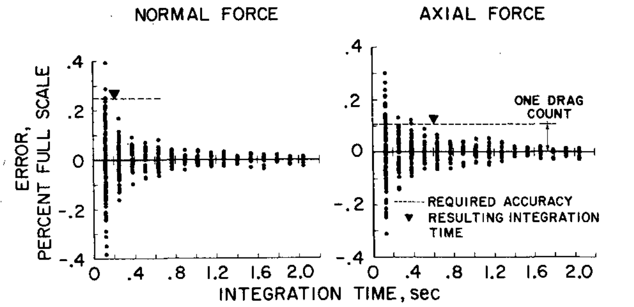


**Fig. 7 Effect of integration time on mean error of balance forces on a lightweight fighter model.**

speeds. In the past, this problem has been solved in various ways. One commonly used method in continuous-drive wind tunnels is to use a combination of lowpass filters ($f$ cutoff = 1.0 to 10.0 Hz) to remove the high-frequency content and then use multiple samples to obtain a mean reading. Others use various schemes to integrate for a period of time, e.g., 1 s. Modern, short-run-duration facilities with high-speed data acquisition systems can numerically integrate for a period of time until the reading is constant within some specified accuracy. Note that time required by all of the above techniques to determine the true mean. Even when a single sample of a filtered signal is recorded, the time constant of the low-frequency pass filters must be considered.

Figure 7 shows the error of the mean force (in percent of full scale) as a function of integration time for the forward normal force and axial force in Fig. 5. These results are for an angle of attack near maximum lift/drag ratio where maximum accuracy is required and where dynamics are relatively low. The many error points were determined by integrating for the time periods shown, different portions of a 32-s record, and then comparing these mean values to the mean determined by integrating the entire record. There are $32/T$ points at each of the discrete integration times shown in the figure.

The accuracy frequently quoted for normal force is $\pm 0.25\%$ of full scale. Thus we see in Fig. 7 that to assure this accuracy, the signal must be integrated for approximately 0.25 s. The drag coefficient accuracy of $\pm 1$ drag count as shown in Fig. 5 corresponds to an axial force accuracy of approximately 0.1% of full scale for this balance, angle of attack, and model combination. To assure this accuracy, the axial force signal must be integrated for nearly 0.5 s.

#### Experimental Evaluation—Pressure Test

Static surface pressure measurements, along with static force measurements, comprise a significant portion of the data recorded in transonic wind tunnels. As previously shown in Fig. 2, these pressures can have significant dynamic content.

To illustrate from actual data the integration time required to measure the mean pressure to some specified accuracy, the signals from flush-surface-mounted fluctuating pressure transducers were integrated for various periods of time. The results are shown in Fig. 8 for the three types of flow encountered transonically on a wing-attached turbulent flow, an unsteady shock wave, and separated flow. These data were recorded on the wing of an F-111 model at $M = 0.85$ while experiencing moderate buffet. The techniques used to determine the error relative to the true mean are the same as those used for the force balance data in Fig. 7. Each point is a measured estimated mean value obtained from an integration of the pressure time history for the time duration shown.

An accuracy frequently noted for static pressure measurements is 0.5% of the full-scale rating of the pressure transducer used for the measurements. To assure this accuracy in the attached turbulent boundary-layer region of

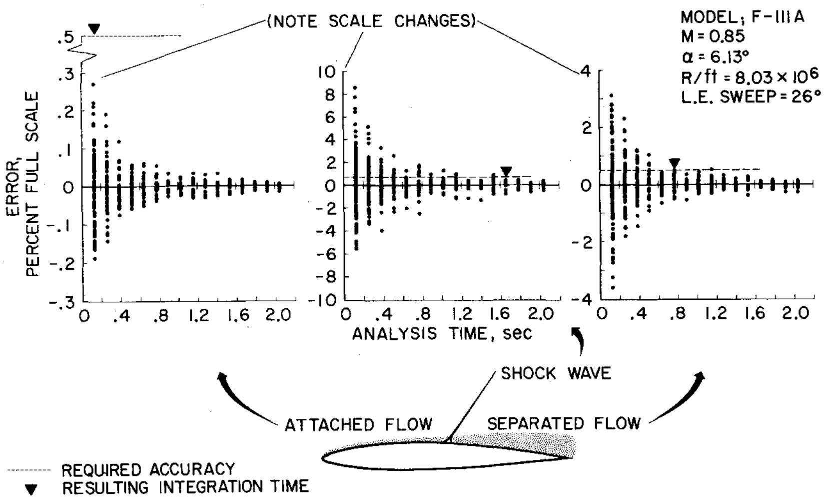


**Fig. 8 Effect of integration time on mean error of pressure measurements on a wing panel.**

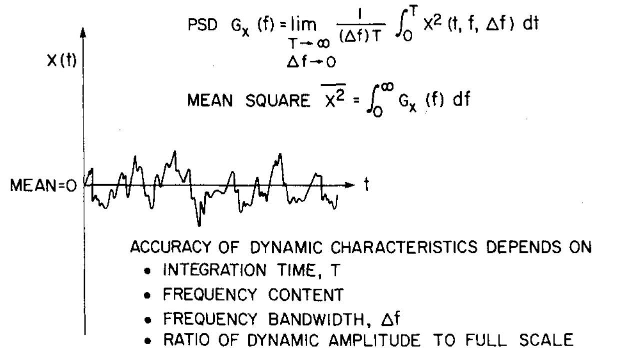


**Fig. 9 Evaluation of dynamic characteristics by mean square and power spectral density.**

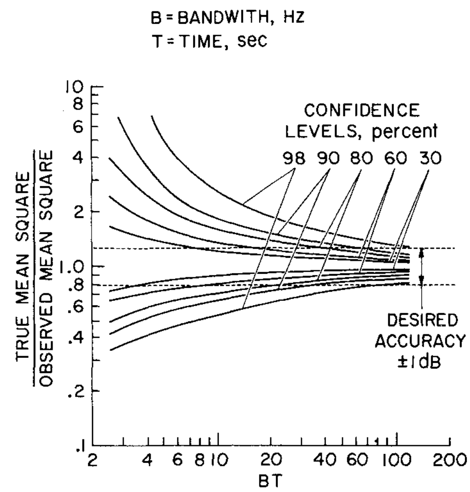


**Fig. 10 Analytical estimation of the ratio of the true mean square to the observed mean square of fluctuating forces or pressures.**

flow would require less than 0.1 s of integration time. The integration time required for the attached boundary-layer flow is short because the dynamic content of the signal resulting from an attached boundary layer is small. To obtain the same 0.5% accuracy in the region of the shock wave would require nearly 2.0 s of integration. In the separated-flow region, approximately 1.0 s of integration is required. The difference in integration times for the shock-wave and separated-flow regions results from the different levels and frequency content of the dynamic signals.

Note that integration of the signal from surface-mounted pressure gages, as done in this example, will result in the minimum time possible to reach a specified accuracy. If, on the other hand, the pressure is routed through small-diameter tubing, some or all of the unsteadiness will be damped by line lag. The dynamic signals can also be damped by analog filters. Nevertheless, a time constant equal to or greater than that shown by the illustrated integration is required to extract the true mean.

## Dynamic Tests

The problem of obtaining accurate estimates of mean-square and power spectral densities of dynamic data is illustrated in Fig. 9. As the equations for the mean square and the PSD show, the accuracy of these measurements depends on most of the same factors that affect the evaluation of the mean value, such as the integration time, frequency content, and the ratio of the dynamic amplitude to the full-scale gage sensitivity. An added factor is the bandwidth of the power spectral analysis. As with the evaluation of the integration times to extract mean values, the analysis of the integration times required for dynamic data was also treated both analytically and experimentally.

### Analytical Prediction of Error

Specific details of the analytical prediction of error in dynamic data as applied to this study are contained in Ref. 7; they are based on the more comprehensive analysis given in Ref. 6.

Figure 10 summarizes the results which show the ratio of the true mean square to the observed mean square as a function of bandwidth times time (BT) for various confidence levels. As an example, a 90% confidence that the true mean square is between 0.80 and 1.25 (about ± 1 dB) of the observed mean square requires a BT factor of approximately 60. If a PSD analysis is being performed to the above accuracy and confidence level, a 5-Hz effective bandwidth would require a 12-s data sample. A 5-Hz bandwidth is frequently used to analyze broadband random data. When the data to be analyzed represents a narrow-band process, such as a model response record, bandwidths as small as 1 or 2 Hz may be necessary to resolve the response peaks in a PSD, requiring data samples of 30 to 60 s or more. If the same confidence of 90% and a ±3 dB accuracy is desired, the analysis time for a 1-Hz bandwidth would be approximately 8 s. As a rule of thumb, a 3-dB error in the estimate of random dynamic stress results in about an order-of-magnitude error in the estimate of the fatigue life of a structure. Generally, as the required confidence level increases and allowable error decreases (true mean square/observed mean square approaches 1), the BT factor increases very rapidly, thereby requiring longer analysis time.

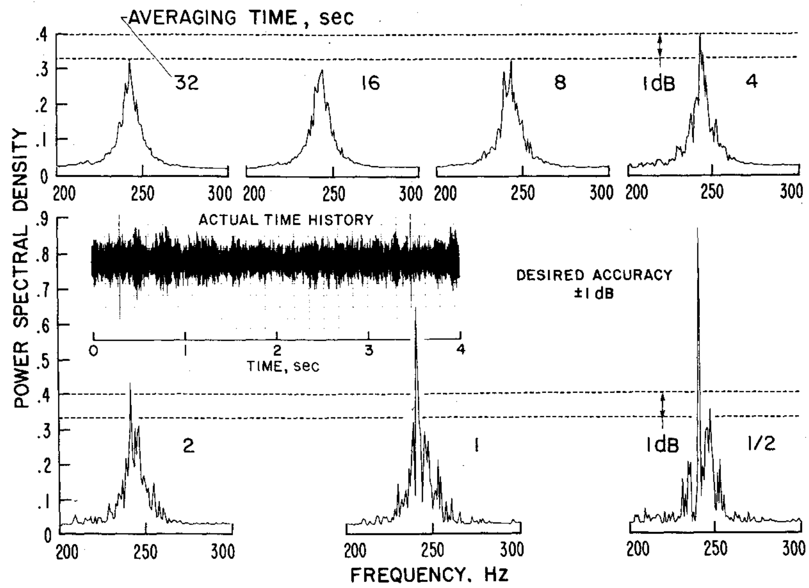


**Fig. 11 Effect of averaging time on the accuracy of PSD measurements of panel response.**

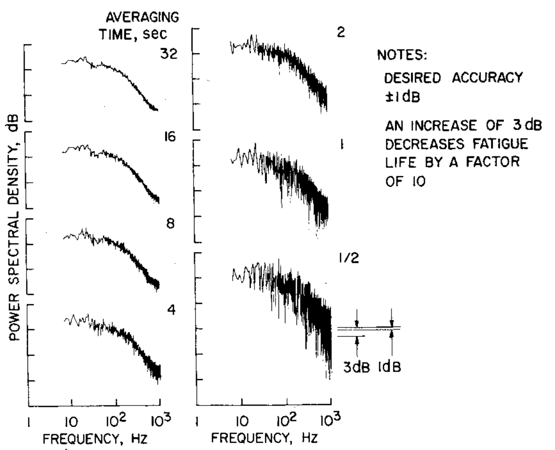


**Fig. 12 Effect of averaging time on the accuracy of PSD measurements of fluctuating pressures.**

### Experimental Evaluation—Power Spectral Density (PSD) Measurements

Figure 11 shows the PSD of the response of an aircraft skin panel as a function of frequency for various analysis times from 32 to 0.5 s. The observed peak is due to only one of several resonant frequencies of the panel. Note that all data in this figure are plotted to the same scale and that the longest analysis time (32 s) gives the most nearly correct estimate of the true PSD. As the analysis time decreases, many extraneous peaks are observed which could lead to the conclusion that many resonant frequencies are present. In addition, as the analysis time was decreased, for the cases shown, the height of the predominant peak increased. Since the 32-s analysis is an average of many short-duration analyses, it is obvious that a 0.5-, 1-, or 2-s record taken at some other time would have peaks lower than those observed in the 32-s record. Thus, depending on when after $T=0$ a short analysis time record is taken, widely varying measurements of the response amplitude can be obtained. For example, for the 1-s analysis time, the amplitude of the response at the resonant frequency differs from the true value by more than a factor of 2. Errors of this magnitude in defining panel response result in large errors in predicted fatigue life (about an order of magnitude when the stress is within the lower position of the $s,N$ curve).

Figure 12 shows the PSD of surface pressure fluctuations, measured on the wing of an F-111A model at $M=0.85$ in the region of a shock wave, for various analysis times from 32 to 0.5 s. The bandwidth of the analysis was 1 Hz. The largest analysis time of 32 s indicates that the fluctuating pressure amplitude for this particular test condition is a smooth function of frequency. However, for analysis of times of 0.5 to 2.0 s, individual spectral estimates can have a spread of 10 dB or more (or greater than a full decade). It is possible that important peaks may be present but cannot be distinguished from the data scatter.

As previously stated, an error of 3 dB in the estimate of the PSD corresponds to about an order-of-magnitude change in the fatigue life of a structure when operating on the lower portion of the $s,N$ curve. A fatigue-life estimate can be in error by several orders of magnitude when stresses are beyond the "knee" in the $s,N$ curve. It is obviously desired, then, that new technology data should be at least targeted for errors within $\pm$ 1 dB. For the data shown, this would require an analysis time of from 8 to 16 s. Failure to achieve at least $\pm 1$-dB accuracy in PSD analyses can have a serious effect on the design of an aerospace vehicle structure, with the attendant problems of excess weight and reduced payload or short life and possible safety problems. Such inaccuracies simply cannot be tolerated in large cost-, time-, and performance-critical programs.

### Run Time Required for Flutter Testing

At least three techniques are in general use in flutter testing: 1) measuring model response to impulse type excitation, 2) measuring model response to a swept frequency forced excitation, and 3) measuring model response to random turbulence in the test stream. In all of these techniques, the accuracy of the results is generally proportional to the length of record available. Flutter testing typically requires run times of from 1 to 60 s, depending on the techniques used, the type of information required, and the risk of model destruction considered acceptable. At the shorter times, the forced oscillation techniques are required and generally provide very little accurate information beyond indicating the presence or absence of flutter. Consequently, the risk of model destruction is greater because the approach to flutter conditions may not be accurately defined. If longer test times are available, the model can be excited by the random turbulence in the airstream. Equipment is available which can accurately determine the aerodynamic damping of many modes of vibration simultaneously. Thus, the approach to a flutter condition and the aerodynamic damping available at any condition can be defined. This type of detailed information

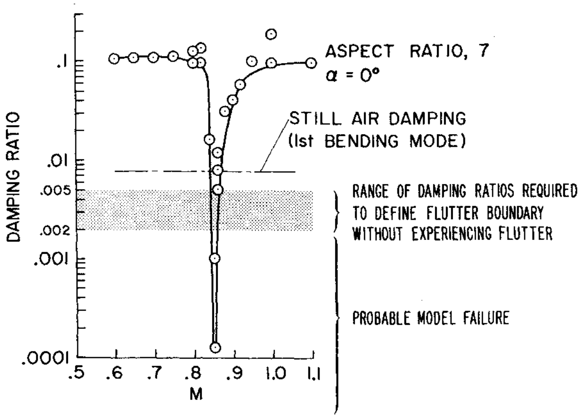


**Fig. 13 Effect of Mach number on total system damping of a straight wing flutter model.**

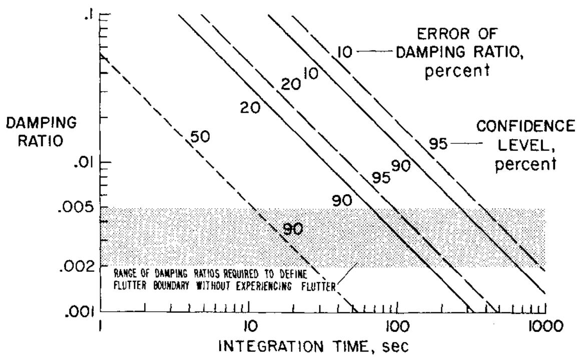


**Fig. 14 Integration time required as a function of damping ratio for various confidence levels and error using Randomdec, $f = 50$ Hz.**

will become more important as advances are made in active control systems that can suppress flutter. Furthermore, the consequences of destruction of a flutter model should not be minimized. Such loss could mean significant program delays while a new model is being built. In addition, if the model is complex, the cost can exceed $500,000.

An example of measured damping ratio as a function of Mach number for a wing flutter model is shown in Fig. 13.[8] For this model, the flutter condition is limited to a very narrow Mach number range near $M = 0.84$ and is characterized by an extremely rapid decrease in aerodynamic damping. This is an example where a model can be placed in a flutter situation accidentally if accurate values of damping are not available. This figure also indicates that damping ratios of 0.002 to 0.005 must be measured to define the flutter boundary.

The integration time required to measure damping using Randomdec is shown in Fig. 14 for various values of accuracy and confidence level. The Randomdec system[9,10] shows great promise for flutter testing involving measurements of damping under random excitation conditions such as would be encountered in a wind tunnel. These values are for a frequency of 50 Hz, a typical frequency for the wing first bending mode of a full-span model sized for tests in an 11- by 11-ft wind tunnel. Lower frequencies would require longer record length; higher frequencies would require shorter record length. To accurately define the flutter boundary without experiencing flutter, it is necessary to determine damping ratios in the range of 0.002 to 0.005 with high confidence. For a typical flutter test, it would be desirable to have 90% confidence with 20% error of the damping ratio. These requirements define a record length of 100 to 250 s as the flutter condition is approached. A damping ratio of 0.01 requires a record 50-s long. Even with 50% error and 90% confidence for a damping ratio of 0.005, more than 10 s is required.

The above values are based on single-degree-of-freedom system and as such are the "best case." The presence of additional modes will complicate data reduction. It two modes have frequencies that are not well separated, as is typical of bending-torsion wing flutter, the time required to define the system damping will increase significantly.

## Conclusions

An analytical and experimental evaluation of the integration time required to obtain data of the desired accuracy from tests in transonic wind tunnels has been performed. Based on the results presented, it is concluded that typical maximum integration times required for various types of tests are as follows: static force, 0.5 s; static pressure, 1.0 s; flutter, 30 to 60 s; and random dynamic, 10 s.

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