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# A Global Approach for the Identification of Structural Connection Properties


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# A GLOBAL APPROACH FOR THE IDENTIFICATION OF STRUCTURAL CONNECTION PROPERTIES

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## SUMMARY

A general procedure is developed for identifying properties of structural joints. The procedure, which uses experimental response data, is considered general because it is applicable to any size or type of structural system. The present procedure, which identifies characteristics such as damping and stiffness, accommodates both linear and nonlinear joint properties and may process test data measured at arbitrary stations on the structural system. The method identifies joint characteristics by performing a "global" fit between predicted and measured data. It overcomes limitations of previous methods in that it can better deal with parameter-dependent constraints (e.g., gaps). The method is demonstrated with a simplified model of a bladed disk assembly having friction damping and mistuning.

E-5303

## INTRODUCTION

A general procedure is developed for identifying properties of structural joints. The procedure, which uses experimental response data, is considered general because it is applicable to any size or type of structural system. Furthermore, characteristics such as damping and stiffness, as well as nonlinearities in joints, may be identified.

The ability of analyst to construct accurate structural dynamic models, and then perform the subsequent dynamic simulations, often is limited by their inability to estimate the parameters necessary for creating the model. Characterizing structural joints presents a particularly difficult challenge. While present day algorithms, and the computers on which they are executed, may be capable of performing sophisticated analyses of very large and complex dynamic systems, the ensuing results may be only as reliable as the model. Hence, a poorly modeled system, with only approximated structural interfaces and joints, will be unable to represent the actual system response, regardless of the theoretical or computational capabilities.

Since joints usually contribute significantly to the overall system stiffness, damping, and in many cases nonlinearity, it is critical that reliable joint models be made available. For many structural systems the constituent components often may be modeled accurately, but the joints contain considerable modeling uncertainty. Therefore, accurate system response predictions often are highly dependent on valid joint models.

For many types of analysis an accurate model is an necessity, while for others it may not be as important. For example, if the modulus of elasticity of a statically loaded system is in error by 10 percent the resulting displacements will only be 10 percent erroneous. On the other hand, a very small error in a system's eigenvalues may cause order of magnitude differences in the forced response, or a stable system to become unstable.

In the case of discrete modeling methods, such as finite elements, one possibility for developing a more accurate representation of the joints is to refine the mesh detail by decreasing the individual element sizes or by using higher order elements. By refining the mesh, the joints geometrical shape may be represented better, allowing for a more precise description of the resulting stress-strain distributions. Even further modeling accuracy may be obtained by using more sophisticated elements capable of characterizing more complex phenomena such as material nonlinearity, friction, or gaps. Unfortunately, regardless of the refinement of the joint models, the accuracy still will be limited by the accuracy of the basic properties (e.g., modulus of elasticity, moment of inertia, gap regions) used to characterize the joint elements.

Another way of dealing with joint modeling inaccuracies is to accept them, and then perform studies to assess their effects. By doing sensitivity and statistical studies, the impact of modeling difficulties may be determined and statistical attributes such as mean response and variance may be computed. The disadvantage of this approach, in addition to its computational intensity, is that the modeling problems never are resolved and an improved joint model never is created.

The choice approach for managing joint modeling inaccuracies is to actually identify and then correct the problems. The general field which provides methods for resolving modeling problems is labeled System Identification (refs. 1 to 4). In general, System Identification involves the utilization of input and output relations, which normally are obtained experimentally, to determine the unknown or uncertain differential equations used to describe the system. For the more specific problems where the differential equation already is known a priori (e.g., a vibrating structure), the identification problem is reduced to the more specific area of parameter identification.

In reference 5 a comprehensive review of the literature pertaining to damping in structural joints is provided. In this review it is discussed how for many systems the overall system damping is supplied by damping in the joints. Friction and gaps provide beneficial damping but they also make analysis very difficult. The paper also presents the merits of nonlinear joint models. In reference 6 several issues related to uncertain structural parameters are reviewed. These issues include random response due to structural uncertainty, sensitivity to parameter variations, and optimization and reliability.

For linear systems, parameter identification methods which utilize frequency based data (e.g., resonant frequencies, mode shapes, and modal damping) may be applicable for identifying joint properties. In reference 7, Component Mode Synthesis (substructuring) methods are combined with parameter identification procedures to improve the analytical modeling of the structural joints for reduced order systems. In this study, which utilized experimental modal data, substructuring methods were used to reduce the size and complexity of the identification problem. In reference 8, a similar identification procedure is used to determine connection damping as well as the stiffness. The effect of friction damping on an assumed viscously damped system also was assessed. Swept sine tests were used in reference 9 to ascertain the joint properties of nonlinear connections for space structures. Harmonic balancing and Fourier approximation were used to extract the joint parameters from the test data. In reference 10, a mix of analytical and experimental component models were combined to characterize the dynamics of a flexible spacecraft. For this study, joint stiffness and damping properties were ascertained via cyclic loading tests.

Several investigators have attempted to identify nonlinearities in individual structural joints, but only a limited number have confronted the complexities associated with multicomponent connected systems. Previous studies which have addressed connection identification have focused on identifying properties from tests performed on individual joints rather than from coupled system tests. In reference 11, damping and stiffness of a representative space truss joint were studied. In this work results from simplified joint models were compared to results from a complex model which included dead bands, large deformations, and friction forces. It was concluded that in special situations simplified models based on linear springs and viscous dampers may represent the behavior of the more sophisticated joint model. In reference 12, nonlinearities in a structural joint were identified using an approach termed "force-state mapping." This approach involved simultaneously measuring the force on a joint along with its position and velocity. From the shape of the three-dimensional surface generated by plotting force as a function of displacement and velocity, the type and quantitative description of the joint mechanisms were identified.

In reference 13, a technique is introduced for processing noisy test data, and for identifying the parameters in linear dynamic systems. The methods presented there are suitable for identification of structural joints, except that the experimental data must be measured directly at the connection boundaries. In reference 14, a similar method is presented and then applied to a linear dynamic system in which the mass, damping, and stiffness matrices are identified. Except for having the same limitation described for reference 13, of having to measure the data directly at the connection boundaries, this approach is equally acceptable for identifying joint parameters.

In reference 15 a method for identification of linear as well as nonlinear joint parameters is presented. This method is advantageous in comparison with other methods in that the test data need not be taken directly at the connection joint. This is highly desirable, because in most practical situations it is impossible to obtain test data at the connection boundaries, thus rendering other identification methods ineffective. The disadvantage of this method is that very precise measurement data must be taken. When the test data is not precise, the procedure may fail to converge.

The present procedure is applicable to both linear and nonlinear joints and is suitable for processing test data which has been measured at arbitrary stations on the structural system. While the present method has similar overall objectives to those of reference 15, the approach used to achieve the objectives is different. The major difference between the present method and the method described in reference 15 is that the present method performs a "global" fit between the predicted and measured data while the earlier method performs a fit at each increment in time. The advantage of performing the fit at each time increment is that it is computationally very efficient. The disadvantage is that if the results are not accurate at a particular time step, the results at subsequent time steps also will be inaccurate. The present approach, which utilizes a global fit alleviates this problem by removing the dependence on results from previous time steps. The present method also is advantageous because it can better deal with parameter dependent constraints (e.g., gaps).

The present method is demonstrated (see sample problem) with a bladed disk assembly having friction damping. This system was used for the demonstration because it is a relatively complex system and exhibits considerable joint damping. For typical bladed disk assemblies the dominate joint damping originates from blade tip rubbing or from interblade friction forces acting at the blade's shroud locations. In reference 16 an analytical and test evaluation were conducted to determine the performance of turbine blade platform friction dampers for the Space Shuttle Main Engine. A lumped mass model of the bladed disk system, which is similar to the one used in the present study, was used for the dynamic simulations. Reference 17 also discusses friction damping for tuned, as well as mistuned, bladed disk assemblies.

## PROCEDURE

To accomplish the identification of the connection parameters, the complete structural system is excited at various stations along the structure, and the resulting response (e.g., displacements and velocities) is measured. The measurement stations may, or may not, be collocated with the excitation, and the number of measurement stations may, or may not, be equal to the number of input excitations. In general, it is simpler to excite the system with a single input, and then measure the resulting response at multiple stations. It is required that both the input be known and the output be measured, regardless of the number of stations. As mentioned previously, the present procedure is advantageous over previous methods in that the response measurements need not be stationed directly at the connection boundaries, but instead may be established at any convenient position on the system.

The present procedure involves four major steps (fig. 1). First, experimental data is obtained by applying the specified excitation, or initial conditions, to the system and measuring the resulting response. In Step II, an approximate analytical model is used to compute estimates of the output at the stations where the experimental data was measured. In Step III, updated connection parameters are identified which minimize the differences between the measured and predicated output data. The procedure is repeated from Step II until the identified connection parameters converge. These procedural steps are described more fully below:

### Step I

The test setup for obtaining the experimental data is determined by convenience and the characteristics of the individual connections. In practice it is only possible to locate exciters or preload at locations on the structure where there are direct access and ample clearance. While the present method does permit arbitrary location of the input excitation, it is required that the input transmit energy through the connections and that every type of connection characteristic is exercised adequately. For example, if the connection contains friction damping and gaps, the excitation must be located so there is relative displacement at the connection boundaries and so that the connection force is large enough to close the gap for at least part of the time. In some situations, applying an initial impulsive load or displacement, and monitoring the free response decay, may be advantageous over a forced response excitation.

The quantity of available experimental response data is dependent on the number of measurement stations and the number of time steps (data points) taken at each station. The required location and number of response measurements are determined primarily by the desired accuracy of subsequent computations. It is expected that increasing the number of measurement locations or the number of measurements at an individual location will be beneficial for identifying the connection parameters. Obviously, it is simpler to obtain additional data at measurement station than to increase the number of stations. The effect of using different quantities of measurement data is addressed in the sample problem.

## Step II

An approximate analytical model based on estimated connection properties is used to generate predicted response data at the measurement stations. Any type of analytical model is appropriate as long as it adequately characterizes the structural components and is capable of producing response data at the measurement stations. The model must precisely characterize the components because a basis for the identification procedure is that the component models are accurate and all of the modelling discrepancies are contained in the connections. If modelling discrepancies do exist in the component models, incorrect connection properties may be identified (see example).

For medium sized structures a finite element model could be appropriate for modelling the structure, while for larger systems a mixed finite element modal model may be better suited. Since it is necessary to integrate the structural equations of motion to obtain not only the response data, but also the parameter sensitivities (Step III), it is desirable from a computational viewpoint to keep the size of the model to a minimum. For the present study, a relatively simple, lumped parameter model is used.

## Step III

The connection parameters are computed by minimizing the differences between the predicted output obtained in Step II, and the measured output from Step I. The parameters are computed iteratively from:

$$\{p\}^{i} = \{p\}^{i-1} + (([S]^{T}[W][S])^{-1}[S]^{T}[W])(\{u^{p},\dot{u}^{p}\} - \{u^{m},\dot{u}^{m}\})^{i-1} \qquad (1)$$

where $\{p\}$ are the computed connection parameters, $[W]$ is a weighting matrix applied to the measurement data, and $[S]$ is a sensitivity matrix containing the partial derivatives, $d\{u\}/d\{p\}$. $\{u^{p}\}$, $\{\dot{u}^{p}\}$, and $\{u^{m}\}$, $\{\dot{u}^{m}\}$ are the predicted and measured displacements and velocities respectively. Appendix A and reference 8 provides additional discussion of equation (1).

The sensitivity matrix, [S], containing the partial derivatives $d\{u\}/d\{p\}$ is used to relate the response data to the connection parameters. This matrix is expanded as:

$$[S] = \begin{bmatrix} \frac{du_1}{dp_1} & \frac{du_1}{dp_2} & \frac{du_1}{dp_3} & \cdots & \frac{du_1}{dp_n} \\ \frac{du_2}{dp_1} & \frac{du_2}{dp_2} & \frac{du_2}{dp_3} & & \\ \vdots & & & \ddots & \vdots \\ \frac{du_q}{dp_1} & \frac{du_q}{dp_2} & \frac{du_q}{dp_3} & \cdots & \frac{du_q}{dp_n} \\ \frac{d\dot{u}_1}{dp_1} & \frac{d\dot{u}_1}{dp_2} & \frac{d\dot{u}_1}{dp_3} & \cdots & \frac{d\dot{u}_1}{dp_n} \\ \frac{d\dot{u}_2}{dp_1} & \frac{d\dot{u}_2}{dp_2} & \frac{d\dot{u}_2}{dp_3} & & \\ \vdots & & & \ddots & \vdots \\ \frac{d\dot{u}_q}{dp_1} & \frac{d\dot{u}_q}{dp_2} & \frac{d\dot{u}_q}{dp_3} & \cdots & \frac{d\dot{u}_q}{dp_n} \end{bmatrix}$$

where 'n' is equal to the total number of unknown connection parameters, and 'q' is the number of response degrees of freedom. Note that $\{u\}$ and $\{\dot{u}\}$ are vectors containing response displacement and velocity data for the entire time history.

The sensitivity matrix is computed by perturbing each of the connection parameters, one at a time, then integrating the equations of motion to determine the resulting response. For example, a perturbation of the $i^{th}$ parameter is used to generate the $i^{th}$ column of the sensitivity matrix. Computationally, the generation of the sensitivity is very expensive because the equations of motion must be integrated for each parameter. Furthermore, since the connection forces are nonlinear, it is necessary to iterate at each increment of the time integration to insure that equilibrium is satisfied.

## Step IV

The identified parameters from Step III are used to update the analytical model. The entire procedure then is repeated from Step II until the identified connection parameters are converged to the desired degree of accuracy.

## SAMPLE PROBLEM

A simplified model of a bladed disk assembly was used to demonstrate the parameter identification procedures (fig. 2). The assembly consists of five blade models each of which are modeled by a two-degree-of-freedom lumped parameter system. Each of the blades are interconnected by a linear elastic spring and friction damper. Each blade also has a tip friction damper. The entire system consists of ten degrees of freedom. While an accurate representation of an actual bladed disk assembly may require many more degrees of freedom, this simplified system may provide valuable insight and certainly is useful for verifying the parameter identification. The model was used to generate the predicted response required for the parameter identification as well as simulated "experimental" data. Subsequently, experimental response will refer to the response which was generated from the simulated "experimental" model.

Initially, the unknown connection parameters were specified to be the coefficients of the inter-blade and tip friction dampers shown in figure 2 as parameters 1 to 10. For simplicity, the friction damper elements were modeled to simulate pure sliding (as opposed to friction with sticking or friction in series with stiffness, etc.). A value of zero was used as an initial estimate for the friction coefficients. 512 time steps and two measurement stations, located at degree of freedom 1 and 4, were used for the identification. Some of the more sophisticated friction models, which also could have been used, utilize a spring in series with the friction force as well as gaps. For actual identification problems it may be desirable and necessary to include some of these more complex models.

The transient response shown in figure 3 was obtained by exciting the system with a nonuniform initial displacement. A nonuniform displacement was used so that most of the structural modes would be excited. As required for II of the parameter identification the identical initial displacements were used for generating response data from the approximate analytical model.

In the first iteration (fig. 3(a)) where the predictor model does not yet have any damping, there is very little agreement between the predicted and actual response. As expected, the experimental response decays quite rapidly due to the damping in the experimental model, while the predicted response does not decline at all. By the sixth iteration, there is general agreement between the predicted and experimental data, and after 35 iterations (fig. 3(c)) there is no noticeable difference between the two responses. Since after 3 sec, the transient response is very small, it may be sensible to use some form of windowing (e.g., exponential) to weigh the response data so that the data obtained past 3 sec are weighted less heavily.

Figure 4 shows a comparison among the ten identified parameters for different magnitudes of measurement noise (0, 5, and 10 percent). In general, as the noise increased the accuracy of the identified parameters decreases. When there is no measurement noise, the identified and actual parameters are almost exactly equal. When there is 5 and 10 percent noise most of the identified parameters are in good agreement except for parameters 6,7,9 and 10 where there is considerable disparity. There may be greater disagreement in these parameters because the measurement stations were located at the degrees of freedom corresponding to the first and fourth parameter. There were no measurement stations located at any of the other parameters.

In figure 5, the relationship between the identified parameters and the number of time steps used for the identification are presented (0 percent noise). In contrast to what was expected, as the number of time steps was increased, the correlation between the experimental and identified parameters decreased. When 128 time steps were used for the identification, there is very good agreement between the actual and identified parameters. When 512 time steps are used, there is fairly good agreement, but not as good as when only 128 points were used. The reason for this inverse relation between quality of fit and number of time steps probably can be attributed to the rapid rate of decay in the response data. As previously mentioned, the data past 3 sec (100 time steps) is not very useful since the amplitude of this data is very small. Although the present study uses simulated data, the small amplitude response may still be unreliable because of its dependence on the integration time step.

In figure 6, the identified friction coefficient for parameter 5 is shown for each iteration. A maximum change equal to about one-half the actual parameter was used as a constraint to better stabilize the search for the correct friction coefficient. Although it took many iterations to converge, there was good agreement, for this particular parameter, between the experimental and identified friction coefficient. This was true, regardless of the number of time steps used.

For actual bladed disk assemblies, it is unrealistic to expect all of the blades to be identical. Therefore, it was essential to investigate the effect of having blades of differing properties (mistuned) on the parameter identification process. To perform this study, a normally distributed, 5 and 10 percent random mistuning was introduced into the structural model. The mistuning was implemented by randomly altering the springs used to characterize the blade stiffnesses. The modified spring constants are given in table I. The mistuning was added to the model used for generating the experimental data, but was not added to the model used for the identification.

The transient response, found from the exact model, for three levels of mistuning are shown in figure 7. By comparing the three responses, it is seen that for 5 percent mistuning there is very little deviation from the tuned response, while for 10 percent mistuning there not only is a difference in the magnitude of the response, but also in the phasing.

A comparison among the identified parameters for the three levels of mistuning (fig. 8) follows a similar trend. For the tuned and 5 percent mistuned assembly where the transient responses are similar, the identified parameters are very close to the actual parameters, while for the 10 percent mistuned systems, where the transient response was considerably different, there is less agreement between the actual and identified parameters. Overall, there is very reasonable agreement between the actual and identified parameters for all three levels of mistuning. This result is encouraging considering the desirability of identifying joint parameters for mistuned systems.

## SUMMARY AND CONCLUSIONS

An analytical procedure has been developed which allows for the identification of the structural properties of joints in multicomponent structural systems. The connection parameters, which are determined by performing a "global" fit between predicted and measured data, may be nonlinear, and velocity or displacement dependent. Adequate transient, time domain response data are required for the assembled structural system; the location of data measurement stations is, however, relatively arbitrary.

A reduced order model of a bladed disk assembly with friction damping and mistuning was used to demonstrate the method. Overall, there is very reasonable agreement between the actual and identified parameters for different levels of measurement error and mistuning. In general, the quality of the parameter identification is dependent on the quantity as well as the quality of the system transient response data available. The number of parameters to be identified is not limited, although larger identification problems may require a greater number of measurement stations. While larger problems will required greater CPU usage, the usage should not become prohibitively large except for applications requiring real or fast time identification such as may be necessary for adaptive control.

The procedure shows great promise for improving modeling capabilities in complex structural systems, as well as for enhancing our understanding of structural behavior. Further developments are desirable in quantitatively determining both the reliability of identified parameters and the requiremerts for the test data.

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TABLE I. - MISTUNED SPRING COEFFICIENTS

| Spring | Nominal spring coefficient | 5 percent mistuning | 10 percent mistuning |
|---|---|---|---|
| 1 | 100 | 102.3 | 107.1 |
| 2 | ↓ | 96.9 | 100.0 |
| 3 | ↓ | 94.9 | 99.6 |
| 4 | ↓ | 100.2 | 88.4 |
| 5 | ↓ | 103.8 | 110.3 |
| 6 | ↓ | 104 1 | 100.6 |
| 7 | ↓ | 96.5 | 74.3 |
| 8 | ↓ | 100.7 | 88.6 |
| 9 | ↓ | 102.9 | 117.6 |
| 10 | ↓ | 100.7 | 88.3 |
| 11 | ↓ | 105.2 | 108.4 |
| 12 | ↓ | 98.9 | 96.9 |
| 13 | ↓ | 100.1 | 106.0 |
| 14 | ↓ | 101.1 | 105.1 |
| 15 | ↓ | 100.2 | 119.6 |

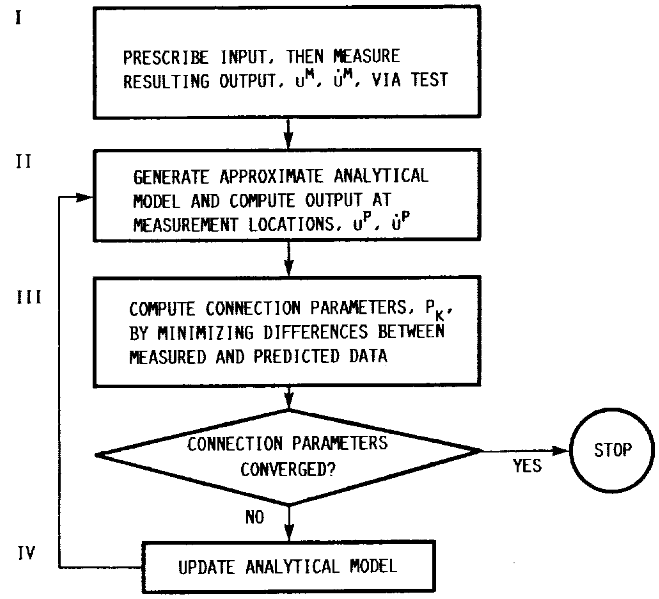


FIGURE 1. - IDENTIFICATION PROCEDURE.

() - PARAMETER, 1-5 TIP, 6-10 MIDCHORD
u - DEGREE OF FREEDOM

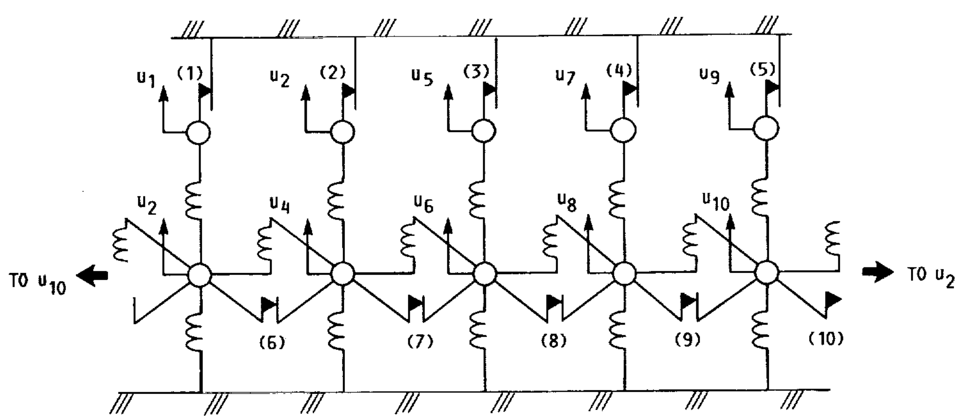


FIGURE 2. - BLADED DISK ASSEMBLY MODEL.

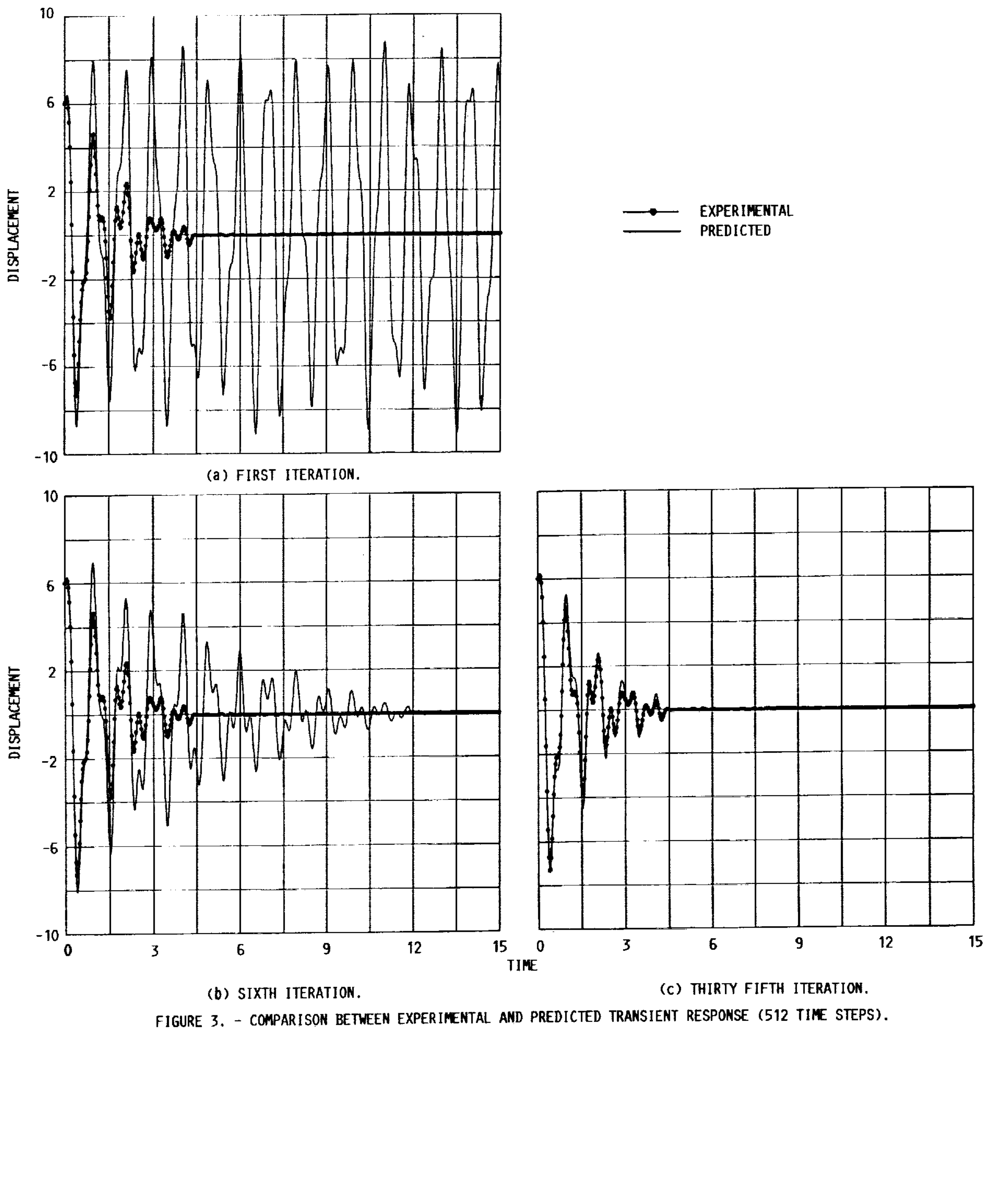


FIGURE 3. - COMPARISON BETWEEN EXPERIMENTAL AND PREDICTED TRANSIENT RESPONSE (512 TIME STEPS).

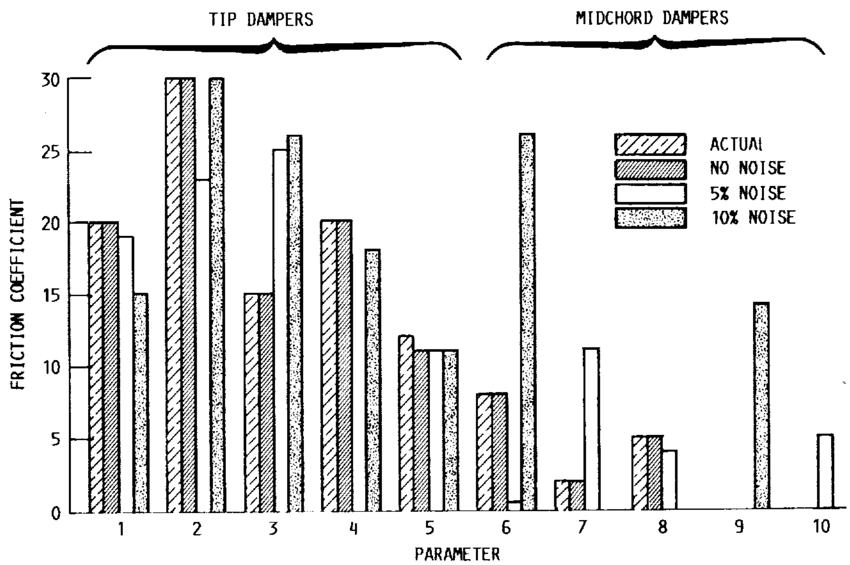


FIGURE 4. - EFFECT OF NOISE ON IDENTIFIED PARAMETERS (128 TIME STEPS).

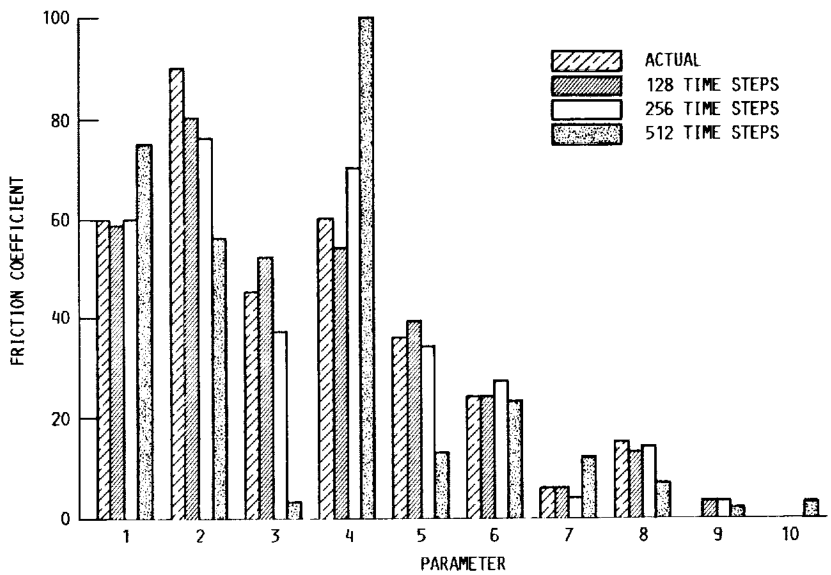


FIGURE 5. - RELATIONSHIP BETWEEN NUMBER OF DATA POINTS AND IDENTIFIED PARAMETERS, 0 PERCENT NOISE.

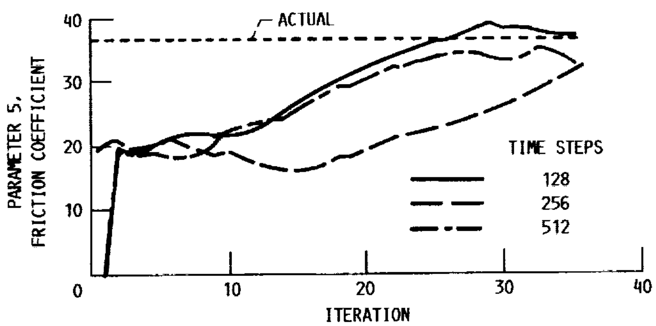


FIGURE 6. - IDENTIFIED PARAMETER AS A FUNCTION OF ITERATION, 10 PERCENT NOISE.

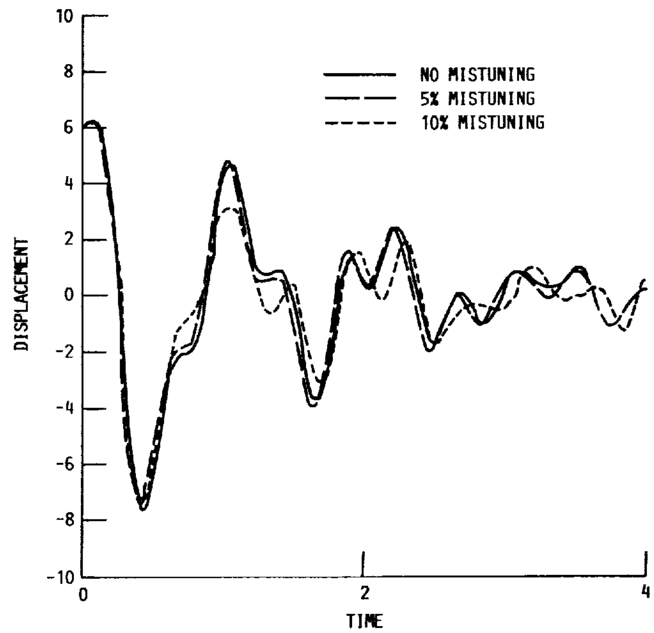


FIGURE 7. - TRANSIENT RESPONSES FOR TUNED AND MISTUNED BLADED DISK ASSEMBLIES.

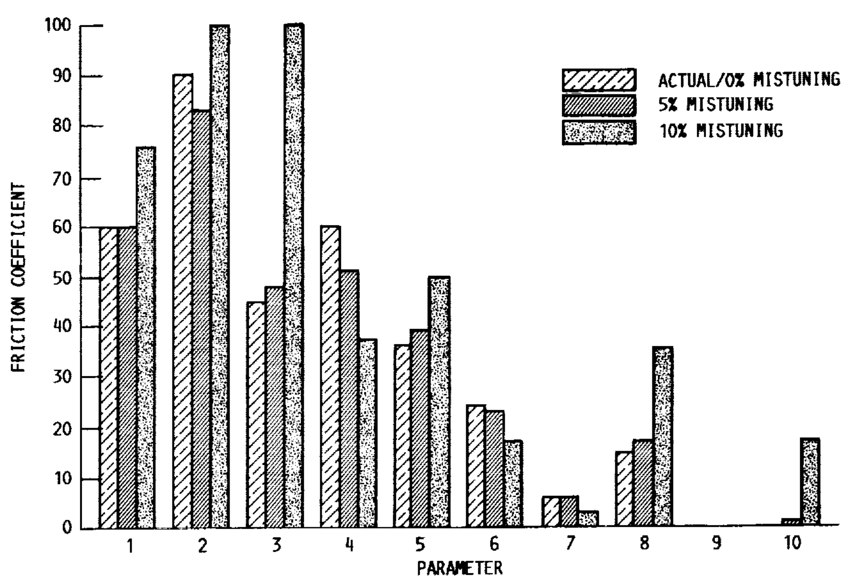


FIGURE 8. - EFFECT OF MISTUNING ON IDENTIFIED PARAMETERS, 128 DATA POINTS, 0 PERCENT NOISE.

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16. Abstract

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