Accelerometer Selection Methods for Modal Pretest Analysis

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Prior to performing a modal survey test, pretest analysis is typically performed to determine the optimal number and location of response measurements and reference measurements. This pretest analysis begins with preparing an accurate finite-element model (FEM). Typically, the test measurement set cannot practically contain more than several hundred degrees of freedom (DOFs), although some recent tests have used as many as a thousand, so any method of pretest analysis should extract the best possible candidate locations from the initial FEM. Automated sensor selection algorithms first up-select to a candidate set of potential degrees of freedom that are several times larger than the final set of sensors. The methods then down-select from this candidate set to an optimal set of sensors. This article presents the methods used to arrive at an initial candidate set for measurements from the perspective of a practicing test engineer.

To increase the chances of a successful test, modal survey tests should often be prefaced with an accurate pretest analysis of the test article. A variety of tools and methods are available to select an optimized set of acceleration response measurements. Pretest analyses begin with a cursory examination of the dynamic FEM to determine the target modes that must be extracted to complete a successful test program. Once these target modes are identified, a mass-reduced test-analysis model (TAM) is generated by determining an accelerometer set (ASET) that uniquely describes the target modes. The number of accelerometers that can be used may be limited by resources such as available test time, budget, and data acquisition channels. Generally, no more than 10 accelerometers per target mode will be necessary to adequately capture all target modes.

While purely analytical methods exist to generate a TAM and a highly efficient ASET that minimizes the ASET and maximizes the quality of extracted modes, practical considerations influence the final ASET development. Analytically generated TAMs may select measurement DOFs that are not physically realizable on the test article. For example, selected measurement DOFs may include inaccessible locations such as internal components, locations that are unreachable on large test articles, or locations that cannot physically accommodate the dimensions of available accelerometers. Manual effort can be spent to remove these inaccessible locations from consideration in the automated selection of the candidate set.

Often, analytically selected measurement DOFs are accessible, but accelerometer installation may still be difficult or cause unnecessary delays in the test program. Examples of such measurement DOFs may include:

- Locations requiring the removal of paneling to access internal components.
- Locations requiring technical support personnel to operate a manlift.
- Locations that are not easily referenced to identifiable features of the test article such as rivet lines, edges or corners; with additional time and effort, such locations may still be identified by a template or laser tracker.

This article discusses the compromises that can be made when developing the TAM to successfully extract all target modes while minimizing the difficulty of installing the sensors. The ultimate figure of merit for a successful pretest is the pseudo-orthogonality defined in the following section. Holding the number of accelerometers constant, a purely analytically derived TAM will produce the best possible pretest pseudo-orthogonality. A TAM that has been adjusted to allow for an easily installed and maintained ASET may have a slightly degraded, but still sufficient, pseudo-orthogonality.

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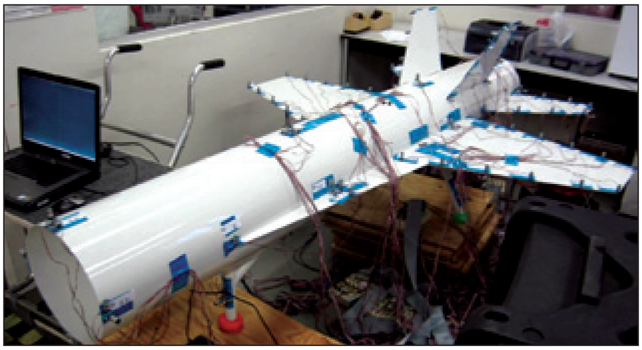


Figure 1. ATA "iron bird" test article.

The following sections describe the pretest analysis process, including the iterative residual kinetic energy (IRKE) method to select the candidate accelerometer locations, the genetic algorithm for down-selecting to an optimal set of accelerometers, and how these relate to constructing the test display model (TDM). The specific test article studied here is the "iron bird," which was fabricated by ATA Engineering, Inc., (ATA) as an internal development and training tool that simulates the dynamics and form factor of a fighter jet. While only the FEM of the iron bird is studied in this paper, the physical test article is depicted in Figure 1 undergoing a modal test.

Analytic Pretest Process

A successful pretest analysis results in an optimized ASET that captures all pretest target modes, as evidenced by the pseudo-orthogonality:

$$\left[O_{12}\right] = \left[\Phi_1\right]^T \left[M_{AA}\right]\left[\Phi_2\right] \tag{1}$$

where $[\Phi_1]$ and $[\Phi_2]$ are full FEM mode shape matrices parsed to the ASET DOF, and $[M_{AA}]$ is the TAM analytical mass matrix. Ideally, the on-diagonal terms of this matrix should be 0.95 or greater, and the off-diagonal terms should be less than 0.10.

The ASET is derived from the test article's dynamic FEM, which may contain several hundred thousand DOFs. Once the target modes are defined, the IRKE method can be used to generate an initial candidate ASET from the full FEM. The IRKE method is particularly useful for test articles with complex form factors and multiple mass simulators, such as large satellites. The IRKE method functions by assessing the modal kinetic energy of all translational DOFs in the test article FEM, and iteratively determining which DOFs are most important with respect to the supplied target modes.[1] The user inputs an initial DOF set (generally very small; it need only be a single DOF) and requests a final number for the candidate ASET DOF. Additional DOFs are selected that are not included in the initial DOF set, and the process is repeated until the final user-requested DOF set is completed. All IRKE analyses presented were completed using NX Nastran™.

Once the IRKE method is completed, the pseudo-orthogonality of the candidate ASET must be checked. If the pseudo-orthogonality does not meet the aforementioned numeric quality, this is likely due to an insufficient number of requested DOFs for the candidate ASET. The user must regenerate the candidate ASET, requesting a larger number until a satisfactory pseudo-orthogonality is achieved.

Once the initial candidate ASET is established, additional analytic methods exist to reduce the ASET to the final measurement ASET if the candidate set is purposely too large. The genetic algorithm (GA) is used frequently to establish a final ASET that is within the available accelerometer budget.[2] As with the initial IRKE analysis, the pseudo-orthogonality of the final TAM must be checked to verify that all target modes will be attainable during testing.

The use of the IRKE up-selection and GA down-selection methods generates an efficient ASET for a predetermined accelerometer budget. To prepare for an efficient test program, a more heuristic approach is needed, and both methods can provide guidance in arriving at a practical TAM. The following section discusses the complete pretest process on the iron bird test article, highlighting this heuristic approach from the viewpoint of a practicing test engineer.

Pretest Analysis of Iron Bird

The iron bird FEM is comprised of 6194 nodes and 6057 elements (mostly quadrilateral plate elements – CQUAD4). Only translational DOFs were considered in the development of the TAM, bringing the maximum possible candidate set to $6194 \times 3 = 18582$. The prior modal test on the physical test article required 105 test DOFs, so this number is used as the target ASET size for this current pretest study. All modes up to 55 Hz were considered target modes (including the six rigid body modes), resulting in a total of 26 target modes based on an analysis of the full dynamic FEM.

The IRKE method was run on the dynamic FEM, with six initial seed DOFs located at the wingtips, tail tips, and fuselage. The IRKE method was run with a requested 1000 ASET DOFs. The pseudo-orthogonality of this result was checked, verifying that this 1000-DOF TAM is nearly identical to the full FEM. The genetic algorithm was applied to this TAM with ASET requests of 105, 95, 85, 75, and 65 measurement DOFs. Based on the pseudo-orthogonality results, the 75-DOF TAM yielded a quality ASET; the result is shown in Figure 2. The pseudo-orthogonality is displayed at the top of the figure and the FEM at the bottom. Values less than 0.01 are not displayed in the pseudo-orthogonality. The arrows plotted on the FEM represent selected accelerometer locations. While the pseudo-orthogonality verifies whether the TAM quality is good, the ASET – generalizing the result displayed in Figure 2 to many different types of test articles encountered by ATA – has the following practical disadvantages:

- The accelerometer spacing is uneven and irregular. This will require individual measurements for locating and marking each accelerometer in the ASET, requiring an excessive amount of test set-up time.
- The selected accelerometer locations may not correspond to easily identifiable hardware features such as rivet lines, edges, or mass simulator edges or corners. Additionally, these locations may not reference convenient local displacement coordinate systems that would otherwise allow accelerometer installations normal or parallel to test article surfaces.
- The selected accelerometer locations may be difficult or impossible to access. Inaccessible locations may include internal components or unreachable surfaces. Other difficult locations may include locations on tall structures requiring technical support (e.g., the use of a manlift and accompanying operator support).

Instead of the fully automated IRKE and GA selection method, the ASET can be selected manually based on test engineering experience. The TDM, ASET, and TAM were generated manually for the initial modal test of the iron bird. The 105-DOF ASET and pseudo-orthogonality are presented in Figure 3. The accelerometers are deliberately located on the edges of the test article and are spaced evenly for a convenient and simple test setup. However, the pseudo-orthogonality indicates that the TAM is not sufficient – and that the ASET may not adequately capture all target modes. To verify that the manual TDM ASET selection is insufficient, the pseudo-orthogonality was checked by including all three DOFs for every node in the TDM. The 243-DOF result is displayed in Figure 4. Since this represents the best-case scenario for the manual TDM selection, a GA reduction is irrelevant until the initial TAM is improved.

Modes 15, 16, 25, and 26, which are plotted in Figure 5, are the modes requiring additional instrumentation. These four modes are wing modes. Both the plotted mode shapes in Figure 5 and the

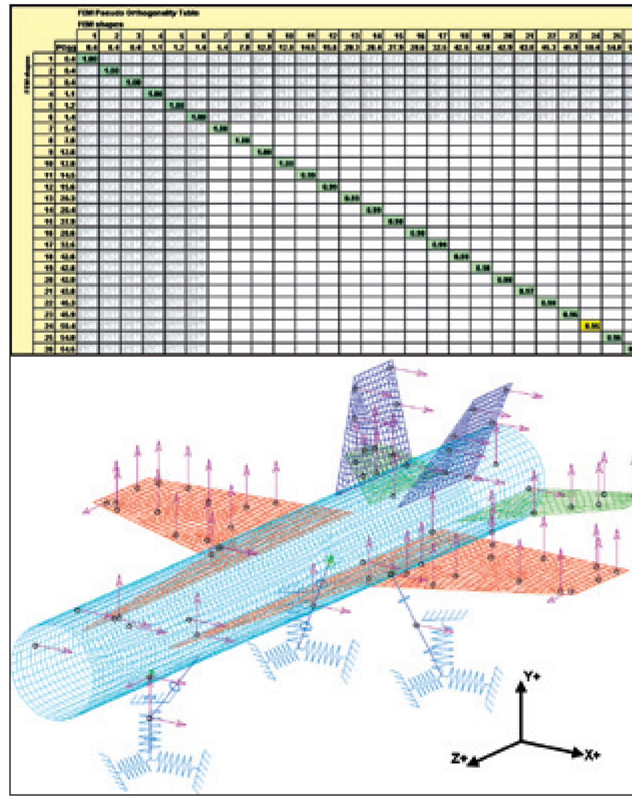


Figure 2. IRKE-selected and GA-reduced 75-DOF ASET; pseudo-orthogonality and FEM are displayed.

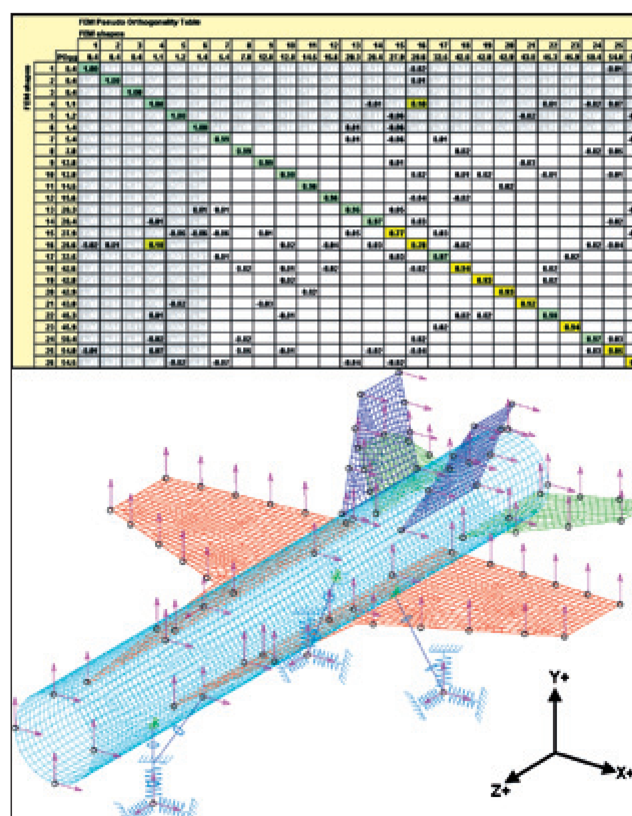


Figure 3. Manually selected ASET; pseudo-orthogonality and FEM are displayed.

IRKE/GA result provide guidance for the next step in the pretest process. Specifically, accelerometers placed manually in the center of the wings and tails should sufficiently strengthen the TAM. If the accelerometer budget must be held constant at 105, the TAM may be improved by adding 126 additional candidate DOFs at 42 regularly spaced locations on the centers of the wings and tails and

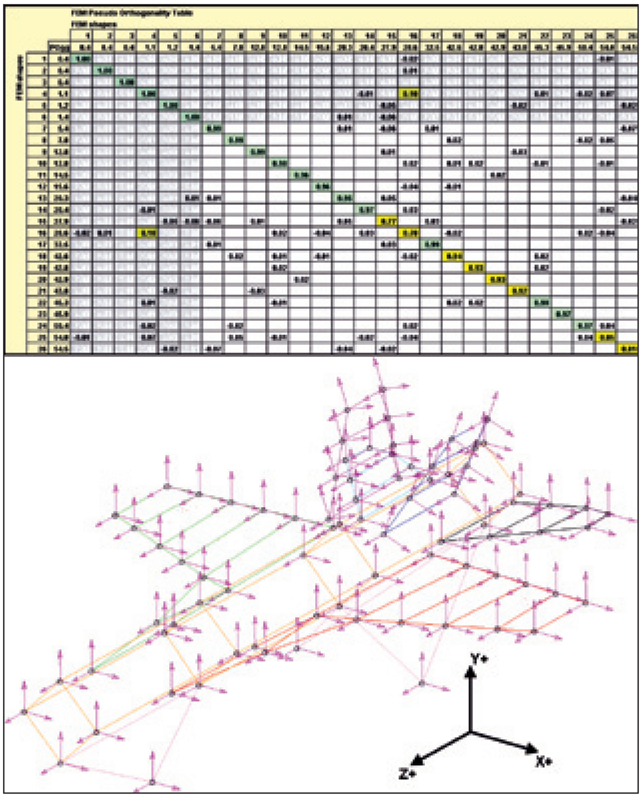


Figure 4. Manually selected ASET, including all three DOFs; pseudo-orthogonality still indicates an insufficient TAM, so a GA reduction would not be productive.

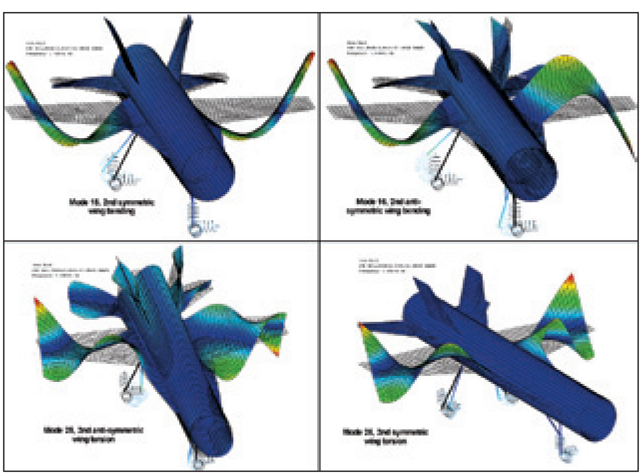


Figure 5. Pseudo-orthogonality of the manual ASET selection indicates that Modes 15, 16, 25, and 26 are not sufficiently represented in the TAM; all four modes are wing modes.

running a GA reduction. The TAM is checked again with this new 369-DOF candidate set, and the result is shown in Figure 6. The pseudo-orthogonality now demonstrates that the TAM is sufficient to proceed with a GA reduction to 105 DOFs.

After adding 126 candidate DOFs to locations in the wing and tail centers, the GA reduced the ASET to the 105-measurement DOF budget. A final pretest iteration is displayed in Figure 7. Predictably, the GA selected DOFs that corresponded closely with the original manual selection, consisting of mostly accelerometers perpendicular to the various iron bird surfaces. The pseudo-orthogonality demonstrates that this TAM is sufficient to capture all target modes. The IRKE/GA result provided guidance in arriving at this final TAM, but since the ASET was still manually selected, none of the drawbacks of irregularity and inaccessibility will be encountered in the test setup. While the final TAM includes 30 more accelerometers than the IRKE/GA-derived TAM, this is a small cost to bear for a convenient, practical, and easily maintained test setup.

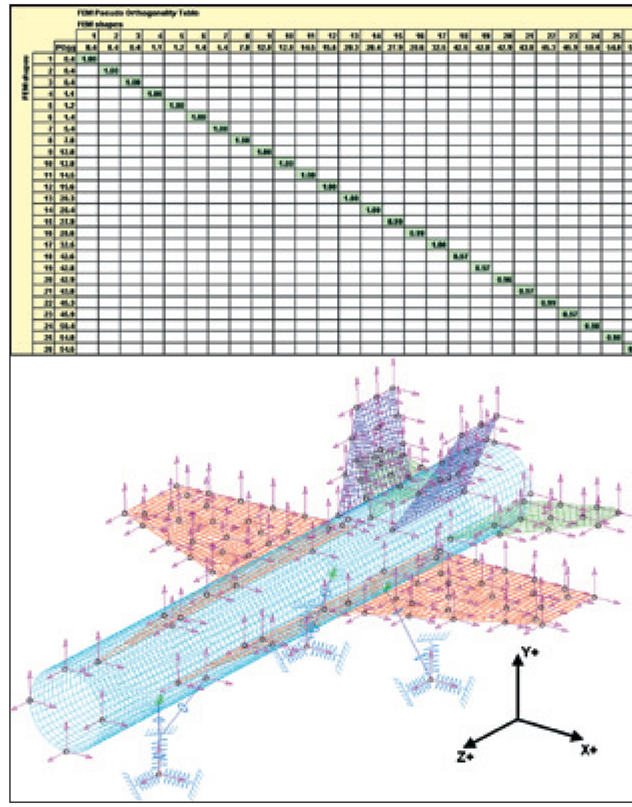


Figure 6. Manually selected ASET, including all three DOFs; additional DOFs were added to the wings and tails, and the pseudo-orthogonality indicates sufficient TAM.

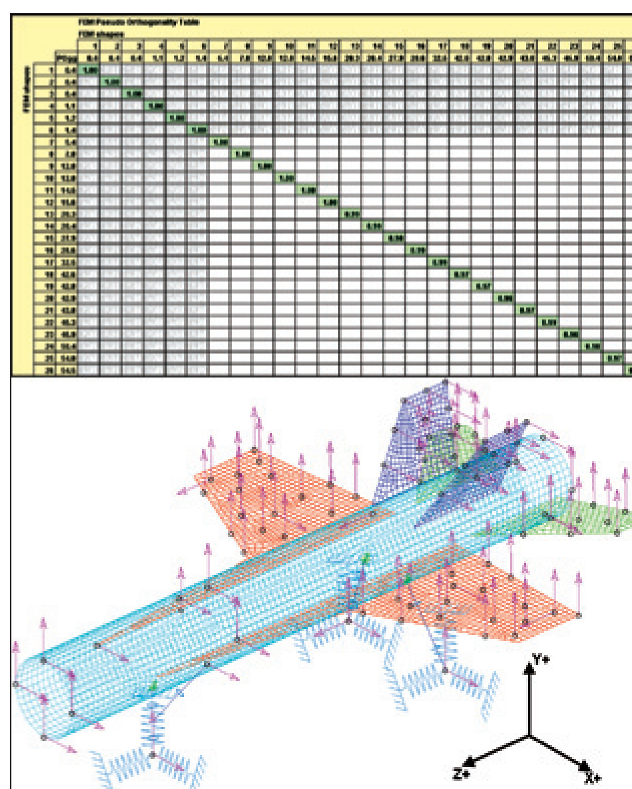


Figure 7. Final ASET, derived from the manual 369-DOF TDM with accelerometers added to the wings and tails and then reduced via GA.

The four TAMs are summarized in the following list as well as in Table 1:

- IRKE/GA-selected ASET, 75 DOFs (Figure 2).
- Manually selected ASET, 105 DOFs (Figure 3.
- Manually selected ASET, 243 DOFs. All three translational DOFs from every TDM node were included to check the viability of

any possible manual TDM-derived ASET (Figure 4).

- Manually selected ASET, 369 DOFs. Additional candidate DOFs were added to the wings and tail sections, and all three translational DOFs from every TDM node were included (Figure 6).
- Manually selected ASET, reduced via GA to 105 DOFs (Figure 7).

Table 1 condenses the four results studied above by displaying only the on-diagonal pseudo-orthogonality results and the FEM/TAM frequency comparisons. The IRKE/GA result clearly produced the best TAM, as evidenced by the pseudo-orthogonality. Additionally, a fully manual ASET selection resulted in an insufficient TAM. Studying the IRKE/GA result was useful to augment the manual and heuristic development of an ASET that would be sufficient to capture all target modes. While TAM 5 (Figure 7) requires 30 additional accelerometers, it has a comparable pseudo-orthogonality to the IRKE/GA result and is both sufficient and practical for a successful test program.

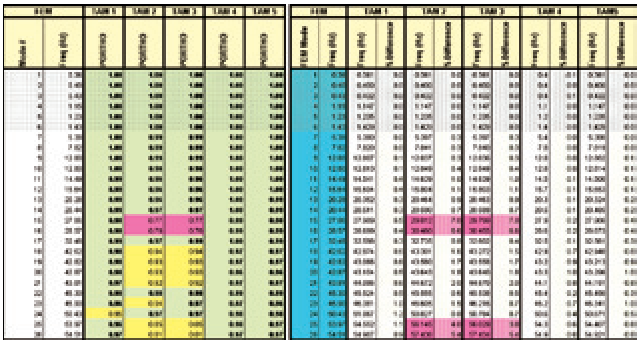
Further manual iterations on the TAM were not completed for this article, but the IRKE/GA result suggests two additional modifications to bolster the pseudo-orthogonality and perhaps even lower the channel count. First, accelerometers may not be needed along the most inboard locations on the wings. Second, the mid-section of the fuselage could possibly be de-emphasized, though additional accelerometers may be placed toward the fore and aft areas of the fuselage.

Discussion

The analytic tools for pretest, such as IRKE and GA, can guide a manual pretest process. A flowchart depicting the complete analytical and manual TAM development process is shown in Figure 8. The pretest analysis can take either an analytic path, with later adjustments influenced by practical test program considerations, or a manual path that is influenced as necessary by the analytic results.

This article has focused on the iron bird test article, but actual pretest analyses require collaboration with the customer – the owner of the test article. In the iron bird study, all 26 modes below 55 Hz were accepted as target modes of equal importance. Other test articles may have modes of variable importance that can affect the manual ASET selection. For example, if the iron bird fuselage breathing modes were determined to be of low value (due to future correlation efforts or relatively high modal frequencies), additional DOFs may have been subtracted from the ASET. This hypothetical determination, which would be made with customer and analyst concurrence, has the advantage of reducing the size of the ASET.

Table 1. Condensed TAM results.



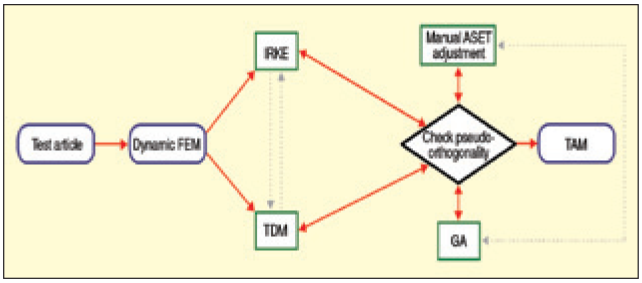


Figure 8. Flow chart depicts pretest process; broken lines indicate that analysis results can influence manual TAM development and vice versa.

Additionally, should such a determination be made, the selected ASET may still be sufficient to visualize the target mode shapes. This is checked initially through observation of the analysis modes. TAM 2 has sufficient measurement DOFs to visualize the second-wing torsion modes, but if TAM 2 was used in an actual test, test engineers could not expect the final test-extracted mode list to pass rigorous orthogonality checks. The importance of such a data-quality check (successful visualization of all target modes and perhaps a high-quality modal assurance criteria check) is again subject to negotiation between the customer and analysis engineers, with the goal of having a successful yet practical test program.

Measurement DOFs that may be difficult or time consuming to install, such as those requiring manlifts or test article disassembly (and the accompanying customer technical support), should also be considered for exclusion from the ASET if the TAM results allow for such a compromise. The customer should work with the test engineers prior to the test program to provide as much information, including drawings and pictures, about the test article as possible. Test engineers and the customer should be cognizant of the additional time and resources required by both parties for accelerometers that are difficult to install and maintain.

In the iron bird study, a generic algorithm was used to reduce the manual TDM set. Additional manual DOF rearrangements and pseudo-orthogonality checks may be performed to further improve the ASET. Like with the IRKE method, the GA may produce a highly efficient, but irregular, ASET, and manual adjustments should be made to regularize and simplify the final ASET – within the constraints of a sufficient TAM.

References

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