The International Journal of Analytical and Experimental Modal Analysis v 7 n 2 p 65-73 Apr 1992

IMAC 10 KEYNOTE ADDRESS: MODAL ANALYSIS: A PERSPECTIVE ON INTEGRATION*

by J. Leuridan, LMS International

ABSTRACT

"Noise and vibration are not invented here!". Undesirable structural dynamics behavior is normally experienced on final assemblies, by which time the underlying cause of the problem is difficult to solve intuitively. Solving the problems classically involves the partial breakdown of assemblies and the application of various structural dynamics testing and analysis procedures, modal analysis being just one of them. Preferably, noise and vibration problems should be avoided by designing the product right the first time, by the use of various integrated analysis and testing disciplines, from the component level to the final assembly. Such an approach is referred to, in a broader sense, by themes as concurrent engineering, forward engineering, simultaneous engineering . . .

This paper looks into the role of modal analysis in a more global approach to engineering for optimal structural dynamics behavior. Modal analysis technology must evolve further in support of a better integration with other techniques for structural dynamics testing and analysis to solve design problems with interrelated vibration, noise and fatigue performance requirements. The likely evolution of structural dynamics testing systems to meet the requirements of more integrated engineering are discussed. Finally, the concept of technology co-development through the European research programs ESPRIT, BRITE, and EUREKA is reviewed.

1. Introduction

A review of previous IMAC keynotes addresses reveals that the need for integration is a high priority for the modal analysis community, as the following quotes show. Integration between analytical and experimental structural dynamics: "The experimental data base will be integrated into the overall Computer Aided Engineering (CAE) effort to help update or correct the existing finite element analysis or to build new models based on experimental data" - Prof. D. Brown, IMAC-1. The integration of various test and analysis activities: "A self contained test station for vibration testing must be developed" - Prof. S. Ibrahim, IMAC-3. On modal analysis being a component to solve structural dynamics problems: ". . . modal analysis is no miracle remedy, it should be used in conjunction with other tools, taking into account the fundamental assumptions of modal analysis" - Prof. R. Snoeys, IMAC-5; and so on.

Certainly many advances during the past decade have contributed towards substantiating this aspiration for integration. The hardware available for executing structural dynamics testing and analysis has evolved from stand-alone hardwired instruments to computer based systems. As a controller they use either a computer workstation or a PC (which has been around for barely 10 years!). The former have put the technology of testing and analysis on the computer platform which over this period has become the preferred platform for engineering design and analysis. The latter have enabled a low-cost solution to modal

Dr. Jan Leuridan, LMS International, Interleuvenlaan 65, 3001 Leuven, Belgium

**Revised version of the IMAC 9 kenote address.*

Final manuscript received: January 15, 1992

analysis and have contributed to its proliferation. The data acquisition front-ends, analyzers and plug-in-boards used by those systems for data acquisition and signal processing have become flexible, powerful and scalable to user requirements. These systems address the needs of both small and large testing laboratories, and the integration of all aspects of structural dynamics testing: acoustics, vibration and modal characterization, fatigue and reliability simulation.

Techniques for using finite element results to direct modal tests, and the use of the results of modal testing to qualify and improve finite element models have advanced significantly. Successes have been achieved, several products are commercially available, but some skepticism prevails (to some extent justified) as to their general applicability and the required user experience. Other areas where technology is starting to evolve at an accelerated pace are the integration of the structural dynamics characterization in control applications of flexible structures, the development of better models to relate acoustics and vibrations, and vibro-acoustic testing. Such progress is also taking place in diverse fields as optical (holographic) testing techniques, the development of mechanical environment testing procedures that accurately reflect all the situations that a product encounters during its life cycle-rather than a fragmented set of them, and a renewed interest in acoustic fatigue, amoung others.

Of course, significant changes have also occurred when it comes to engineering design and analysis in general. Since the introduction of high-performance graphical workstations onto the designers desk, the use of CAE in the design environment has become widespread. In 1985 some 10% of all design was done with CAE equipment, it is estimated that this will grow to 80% by the year 2000. This decade may well become the age of simulation!

With this evolution, one may wonder whether the future lies in soft-prototyping, rather than the traditional approach of 'Test-Analyze and Fix' on real hardware. The answer may not be simple. Indeed, the challenges of the design of new products with improved structural dynamics performance will evolve around the application of more complex materials, the reduction of development time, increased flexibility to faster changing market trends, increased functional and operational performance in less homogeneous, more hazardous environments, and realization in less volume at smaller cost. Naturally, CAE will play a major part in realizing such goals. Yet those design challenges will introduce new unknowns, and therefore the assumptions in the modelling process may become more and more precarious. Testing in general, and experimental modal analysis specifically, will remain, therefore, a vital function in engineering for best structural dynamics performance, however with a defined requirement for more integration with design and analysis.

2. Modal Analysis. A Piece of the Puzzle . . .

Designing for optimal structural dynamics behavior, or solving structural dynamics problems in existing designs, demands an understanding of structural characteristics, operating conditions, and performance criteria. Modal analysis in a strict sense refers to a technology to achieve a particular description of the dynamic characteristics of a structure, namely in terms of modes; each one described by a natural frequency, a damping value, a mode shape and some scaling factor. It can be performed with analytical or experimental techniques. In the context of integration, modal analysis is viewed as one specific technology that is used together with other techniques to solve ever more complex structural dynamics problems: a piece of the puzzle, sometimes the essential piece. The objectives to be defined for a modal analysis, be it experimental or analytical, depend, therefore, very much on the total context: operating conditions, such as loadings; and performance measures, for instance vibration, acoustics or reliability.

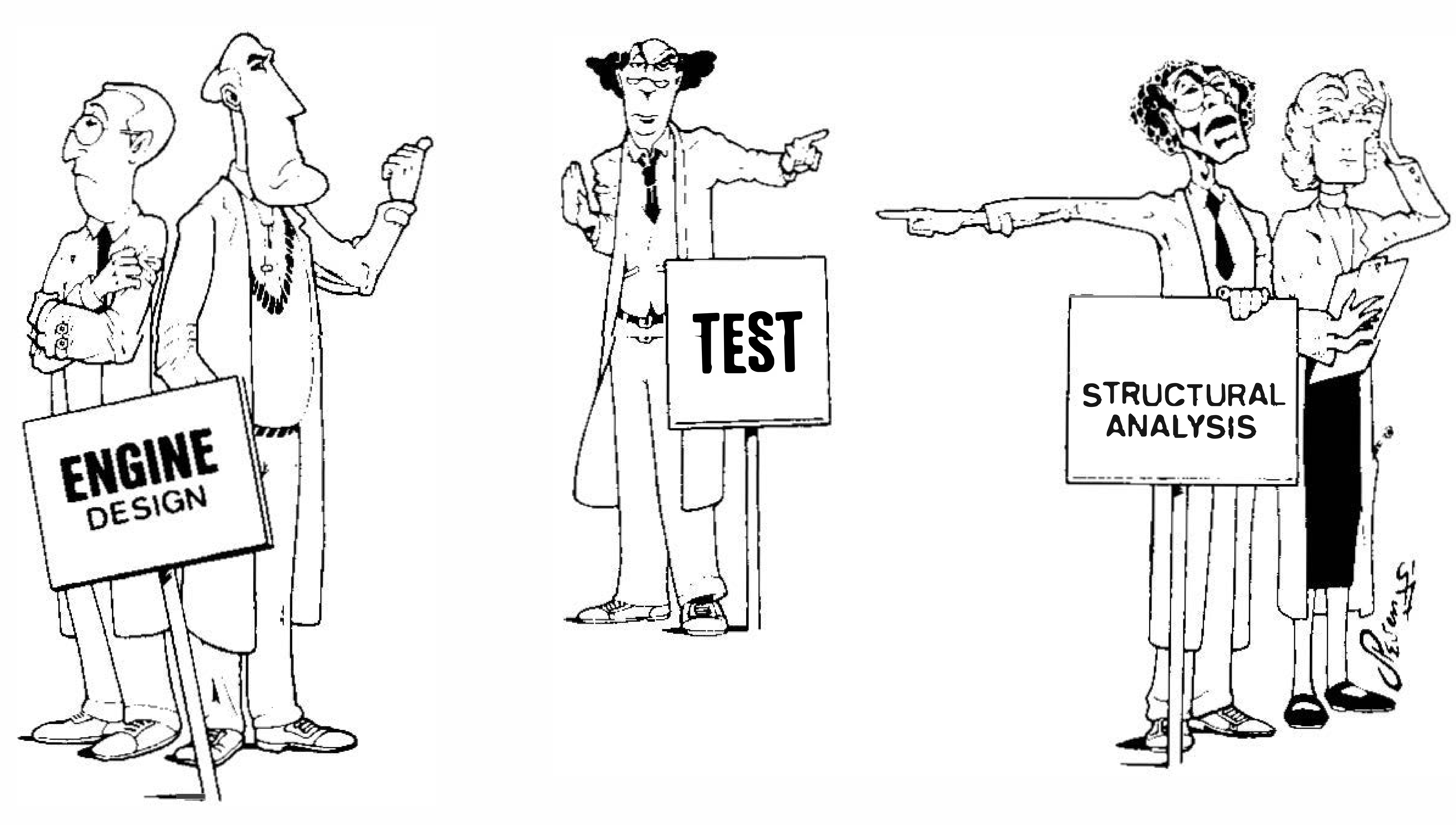
To clarify this, one could take a look at how modal analysis fits (or frequently doesn't fit) into the day-to-day work of engineers in Noise, Vibration, Harshness (NVH) laboratories in the automotive industry. A principal activity of these laboratories is the refinement of complete vehicles to achieve better vibration and noise quality based on prototype testing. A large amount of time is spent on applying routine procedures in order to fully understand the relation between operating conditions and the perceived problems. Operating conditions are assessed from road data and laboratory tests. The latter involves chassis dynamometer tests of various nature (fast run-up/run-down, incremental (stepped) run-up/run-down) as well as road simulation procedures. Data are analyzed in both the frequency and order domains. Performance is measured by vibration levels, acoustic pressure or intensity level, frequently processed in transmissibilities or weighted for subjective qualification. The objectives of these tests are to assess whether problems are resonance related, and further to gain insight into the relation between the measured acoustics and vibrations. Recent developments in the area of structural dynamics testing, such as visualization of operating mode shapes (supported by improved hardware graphics performance) and the correlation analysis of data based on Principal Component Analysis, have contributed to discovering and better qualifying vibration and acoustical problems. It is hardly a role that could be taken over by analytical simulations.

If problems seem to be related to particular resonances, and so to undersirable modal characteristics, an experimental modal analysis may well be in order. The objectives of the modal test will depend on the problem to be addressed, and range from.

- the modal analysis of a body-in-white for global modes,
- the analysis of a full body to understand structural behavior of components such as exhaust system, transmission, engine/gearbox mountings,
- the detailed analysis of local modes on selected areas either on a full body or on a body-in-white,
- acoustic (cavity) modal analysis to understand the dominant modes in the car interior,
- the qualification of nonlinear behavior, and its possible quantification.

The requirements and approach to the analysis or test depend on those objectives, but also on what the results will be used for. They may be used merely for animation of mode shapes to gain intuitive insights; to simulate the response for variations of operating conditions: to simulate the effect of structural modifications; to provide feedback to an analysis for correlating with predictions of an FEM analysis and possibly updating the latter; or to serve as input for a computational vibro-acoustical analysis.

The approaches to modal analysis have certainly evolved, and must evolve further, in order to better meet those analysis and test requirements; this will be examined in the following section. The correct application becomes quite a demanding task for the test engineer, whose success in the end is not measured by getting the mode shape on the computer screen, but by solving the problem. In achieving this, it is essential to have an insight into vibration and acoustics, as well as an operational knowledge of varied discipline oriented analysis and testing systems.



Noise and Vibration: Nobody's Problem

From the above situation one can elaborate on the role of structural dynamic testing and analysis in an integrated engineering environment, and not just for car design. First of all, it will be in support of design simu-lation, as many unknowns prevail in a pure simulation, especially when dealing with a fully assembled new product. Insufficient understanding of the various simulation procedures, the characterization of new materials, the use of different construction methods for structures - and more - all generate unknowns and lead to an inefficient use of simulation, and therefore more iterations. A principal role for structural dynamics testing will be in providing the necessary data feedback from laboratory and field systems to support the design and analysis process. Data feedback has to be understood in a broad sense. It refers to material testing results; to the development of simulation criteria and conditions that properly reflect the mechanical environments encountered during a product's life cycle in support of realistic simulation of a product's performance; to system models identified for characterizing components which are too difficult to simulate with mathematical models, or for their verification. It means, essentially, an efficient connection between the Test-Analyze-and-Fix approach (the beloved final resource for fixing problems on an advanced and apparently faulty design), with the design and analysis activity - in order to avoid problems in the first place.

This is where a major challenge lies for users of modal analysis technology - when it comes to integration. Indeed, noise and vibration problems are too frequently not traceable to a fault in any one design stage. They are observed on the first prototype, when all components are connected and operating testing is performed on the assembly. Solving the problem frequently implies disassembling in search for deficient components. Designing the prototype right the first time implies a correct design of the components and an understanding of the assembly process, specifically with respect to the propagation of structural dynamics performance measures. With an increasing trend toward outsourcing of components to incresase productivity, efficient total integration has to be realized through local action. Designing the components therefore demands a correct definition of design simulation criteria and conditions, enabling the desired performance to be designed-in. Furthermore, the definition of a test, enabling the component to be validated correctly for its desired performance, should be included. It goes without saying that such test-for and design-in criteria should consider the assembly process!

3. . . . and a Puzzling Piece

It would not do justice to the hundreds of contributions to past IMAC's to state that modal analysis has not evolved significantly over the last decade. However claiming that it has reached a plateau would deny reality. First of all, the choice of methods, and whether they are sufficient, depends very much on the objectives of executing the modal analysis. No one doubts that a good characterization of the lower frequency global modes of car body-in-white is possible with current technology. With the introduction of automated multichannel measurement technology and procedures, and dedicated transducer systems, the efficiency in doing it has, however, certainly evolved considerably over the last years. The same characterization on a full body becomes however less trivial. Excitation is more difficult and nonlinear behavior may make the task a nightmare! The description of local modes at higher frequency, with a view to correlating with some acoustical problems is still difficult, and may require an entirely different approach.

The 1980's have certainly been a decade in which experimental modal analysis technology has advanced significantly with the development of multipoint random FRF measurements and global curve fitting. These advances have been made available to industry at large and have enabled complex systems to be analyzed more accurately, easily, and frequently at a reduced cost. Yet current technology has its limits, and not only when it comes to such challenges as the Space Station Structural Characterization Experiment. In the search for techniques that can handle nonlinearities; that enable excitation (and therefore better characterization) at an even larger number of points; that improve measurement precision - research institutes have renewed their interest in using sine excitation. Classical techniques such as normal mode testing are revisited, and, in an attempt to merge advantages achieved with the multipoint random methods, variants are being developed: stepped sine excitation and spatial sine testing. From the 1950's, it's back to the future; the 1990's may become the decade of sine testing. Past IMAC's have certainly contributed toward making the end user community aware of such evolutions. It is reassuring also to see the suppliers of modal analysis systems undertaking efforts to make the sine testing technology available on systems that are currently used for multipoint random.

The quantification of the uncertainty of experimental modal identification results as a function of test data precision has not been a high concern to most modal analysis practitioners. This data is clean, that data is noisy, a good curve fit, a bad curve fit; clean, noisy, good, poor, . . ., are feelings, not facts. Certainly, for many modal tests, quantifying (rather than qualifying) the uncertainty of the results is an academic issue. It may be of relevance, however, if the modal model was developed for a component that is used in a coupling problem to predict the performance of an assembly. It is certainly important for applications such as flight flutter testing. Where the results of a modal identification at a given flight condition need to be extrapolated to the expected modal characteristics at a next flight condition to predict possible flight flutter, a variance estimate of the damping of the excited modes is then most desirable! Commonly used global curve fitting methods do not develop variance estimates on the identification results as a function of test data accuracy. Stochastic techniques that process test data into FRF's or directly into modal parameters, and provide quantified uncertainty, should be used. Additionally such techniques enable better resolution for shorter time records, compared to what can be achieved with Fourier Analysis, and as a consequence, they impose less strict constraints for stationarity. The working principle of such techniques has been demonstrated, their operational usage, specifically in real time applications, is, however, limited today by excessive calculation requirements.

The handling of nonlinearities remains a controversial issue. With random testing procedures the effect of nonlinearities can be "linearized", enabling the modal identification, essentially based on the assumption of linearity, to proceed. It is, however, important to understand their existence in qualifying the validity of the identification results. Several practical approaches to detect, identify and model nonlinearities have been developed over the past decade: the application of the Hilbert transform, the measurement of higher order transfer functions, and the identification of the type of nonlinearity based on functional analysis, such as the complex stiffness method. The availability of these methods on commercial systems will increase the awareness of structural dynamics test engineers to such phenomena, which is essential to developing better qualified modal models.

It was pointed out in the previous section that solving a structural dynamics problem, although observed on the assembly, is frequently achieved by modifications at a component level. Conversely, design for acceptable performance therefore demands techniques to simulate the performance of the assembly based on component design criteria, which leads to the area of substructuring analysis and coupling. Significant research has been carried out to realize substructure representations that accurately represent the dynamics of a component for a

Modal Analysis . . . A Puzzling Piece

specified number of modes at a limited number of degrees of freedom. The measurement of rotational degrees of freedom-important for many substructuring calculations-has become more practical, both with lumped added mass type procedures, as well as by the use of transducers measuring angular acceleration which are now available. Substructuring methods should further improve the tracing of component model uncertainty effects through the assembly, in order to assess the accuracy of the final performance predictions. Approaches to the modelling of nonlinearities when coupling components need to be developed further to include efficient solution methods for such problems.

A related problem is the definition of what the component design requirements are to be so that, if they are met, the assembly to which they belong behaves properly, for example in terms of allowed vibrations. These requirements can be developed from a decomposition of the assembly operating responses into component responses. In order to make this decomposition useful at a design level - so as to predict the effects of design changes - a transformation of component responses into component forces is required. Such process is in general referred to as inverse force calculation. Quite some interesting research is ongoing on this topic. Practical applications include the development of desirable noise-vibration transfer functions in car bodies, the optimization of power train matching to a car body, or modal decomposition of operating data.

Another related topic is technology for environmental requirement integration. It aims at developing better ways to integrated the environments that act on a product during its life cycle missions in design, analysis and test, and this in view of verifying the environmental impact on performance. In the handling of the mechanical environment - vibration, shock, noise - modal analysis is of interest at three levels; the development of platform independent descriptions of such environment, the use of transfer models to predict the propagation of environments through assemblies, and the development of equivalent descriptions of such environments. The characterization of an environment (normally measured as operating responses) so that it is independent of a particular platform involves an inverse force calculation based on some system model of the platform; modal models are explored for this purpose. The development of equivalent descriptions of environments is useful for several applications. For example, the development of a vibration test for a satellite component so that it is equivalent from a damage or strain point of view to levels generated by acoustical excitation during launch; or increasing the productivity of a product qualification vibration test, by developing a test environment that is equivalent to all environments encountered during the product's life profile mission. In developing such equivalent environments, modal models are important in understanding how in multi-mode systems the equivalence criterion, like damage or strain, can be allocated to the modes, so that this mechanism is preserved in the equivalent environment.

Finally, when it comes to developing vibro-acoustical models, the attainable spatial resolution becomes an important factor, specifically at frequencies in the acoustical range where, e.g., insights into local panel modes are important. 3D holography may become an attractive measurement technology for such applications. A modal test could serve to identify the problem frequencies. The modes are then turned with normal mode excitation and the responses are scanned with a 3D holography systems; the hologram is phase-calibrated by the use of a couple of actual acceleration measurements. At higher frequencies, a modal description may not be appropriate at all, and a different approach is in order. A description of the vibro-acoustical systems in terms of energy coupling and loss factors, so based on Statistical Energy Analysis (SEA), seems then more appropriate. Experimental techniques, such as the Power Injection method, have been developed to a level where they can be applied to develop from test data a statistical energy model that is useful for vibro-acoustical analysis, for example, of a car body, in frequency ranges with high modal density.

Integration. Some System Factors.

The realization of a desirable state of integration of modal analysis in a total engineering approach to solve structural dynamics problems requires more than a continued technology development. It also places some definite requirements on the systems that engineers will use, specifically when it comes to user interaction and data handling.

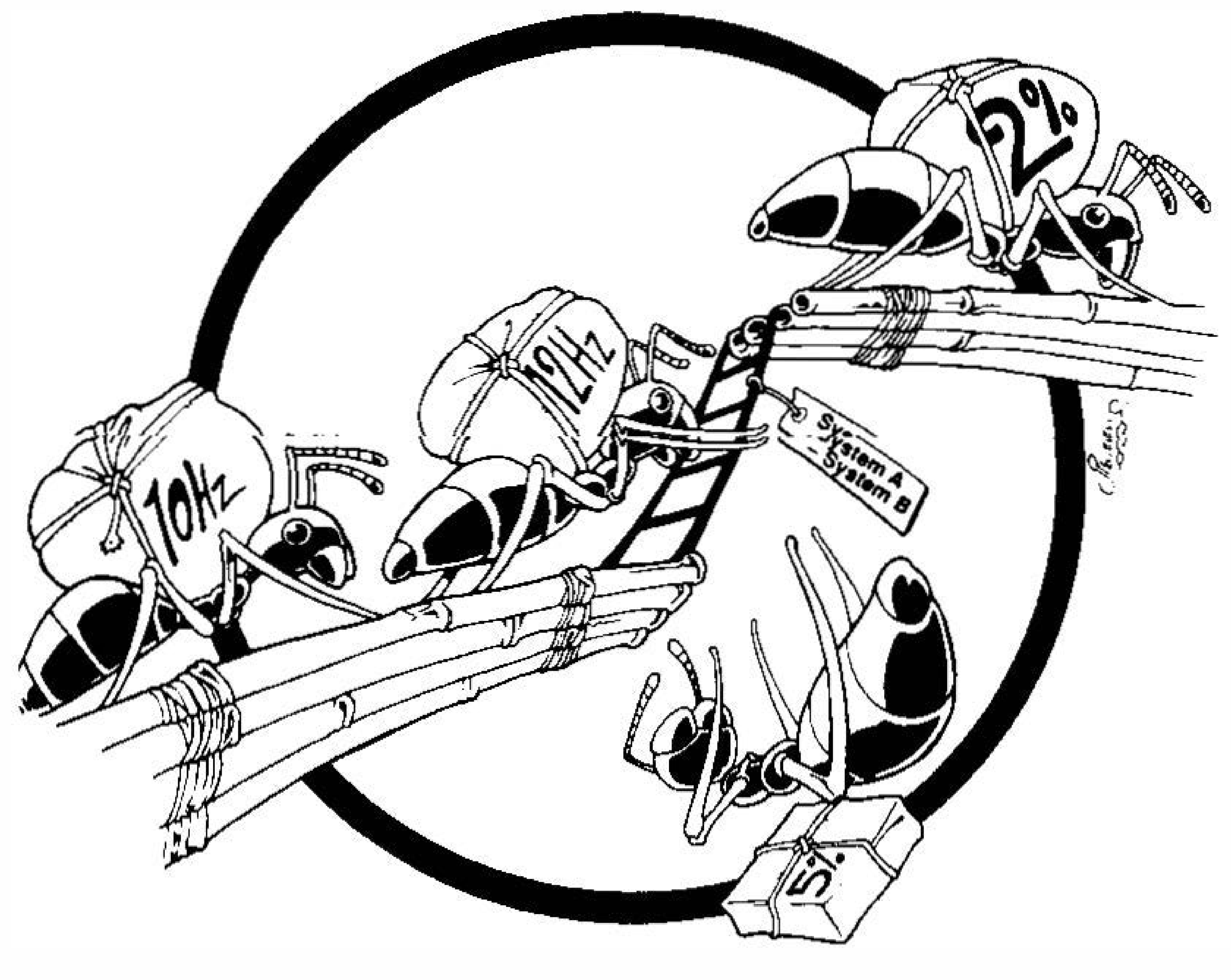
Such systems will be used by users with varied experience, in different types of environments. This requires a scalable user interface, one which can quickly be adapted to the specific needs and skills of the user: the R&D development engineer dealing with structural dynamics seeks flexibility; the development engineer may also deal with structural dynamics occasionally, and therefore seeks straightforward access; the technician involved in executing production type testing seeks dedicated control of procedures that are tailored to a specific type of testing. With the transition from mainly analog based equipment to computer based systems in production testing environments and laboratories taking place today in many industries, the requirements of the latter class of users should not be neglected if the capabilities of new technology are to be properly explored.

In most CAE environments, systems used for experimental modal test and analysis will coexist with other components, such as those for analytical modal analysis, most commonly from a different origin. An "Open System" approach is in order; the various components must be able to interconnect in a coherent framework that is capable of supporting evolution. Efficient use of such a system demands a common design for user interaction, avoiding "to relearn" systems, rather enabling concentration on functionality. Essentially the users and application developers are seeking modularity and standardization. This need is recognized by the computer industry at large, and has resulted in the creation of Graphical User Interface (GUI) standards for computer work stations. A GUI consists of a windowing system, an Application Programmer Interface (API) and an imaging model. An example of such a GUI is OSF/Motif - OSF (Open Software Foundation) is a non-profit organization established in 1988 by HP, DEC, Bull, IBM, Nixdorf and Siemens among others. OSF/Motif consists of X-Windows Version 11 Release 3.0, the Motif toolkit and a user interface language (parts of the API), a Window Manager and a Style Guide. The latter helps the development of application programs with a common look and feel, independent of the particular origin, which is a critical element is realizing open integrated systems.

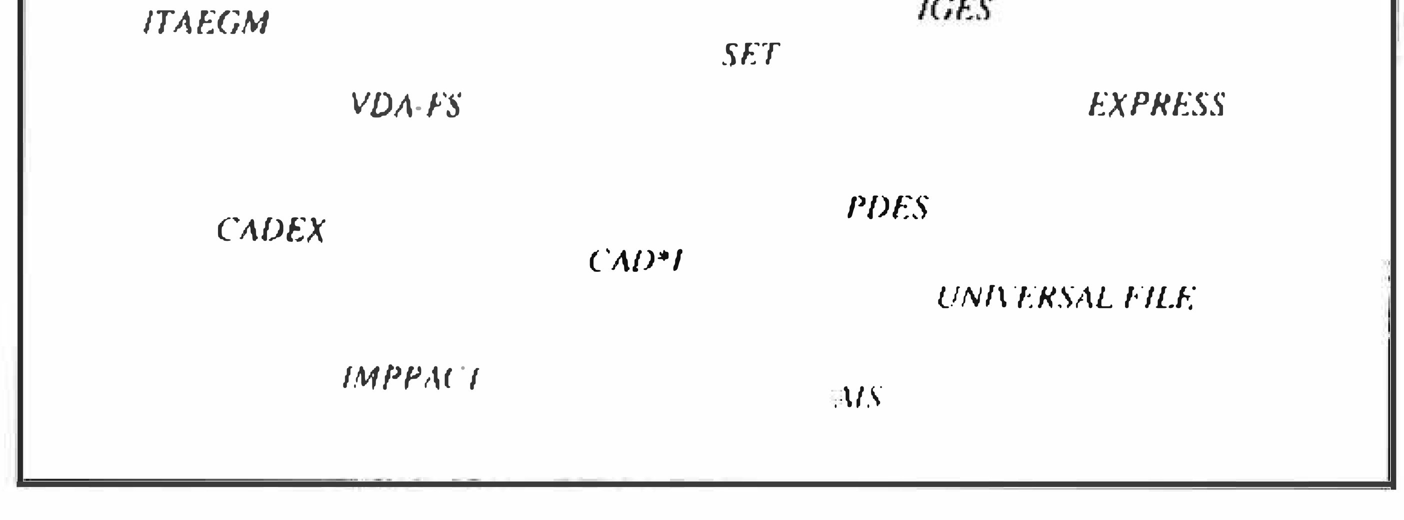
Integration also has a lot to do with data: data models, data representation, data exchange.

The situation today is one far removed from integrated data banks that are accessible by the various discipline oriented software of different suppliers. The answer to this need is standardization for data exchange and data interfacing. There have been strives in the past years to unify the process of data exchange, by moving away from point-to-point interfaces, to mechanisms that enable a multipoint exchange through a common representation, referred to as a "neutral file". As a result of this, one has today as many approaches as there have been committees and projects set up on this: below are some buzzwords that refer to them.

Aimed to create unifonnity, the picture shows a complex reality. There is no clear view on what mechanism will prevail as the standard, and therefore there is no real justification of the investment by



Data Exchange: Lack of Standards



Data Exchange Projects

industry in any one of them. The ISO standardization activity on exchange of product definition and analysis data, STEP (and related technologies and programs such as PDES, EXPRESS, CAD*I, CADEX), is likely to play a major part. It should however include the data representation requirements of the structural dynamics testing and analysis community, which is discussed as part of the application models of STEP, but not likely to be part of the standard less than 2-3 years from now.

With all of this, data interfacing remains suboptimal. It results in an interfaced system, and the replication of data in proprietary data bases. An open integrated system would require a backbone layer of global data which the various discipline oriented components use to share data. Each component of the system could maintain a local data base for proprietary data handling. It is however challenging to define the global data model. With more and more data being generated by testing and analysis, such a global data model will also be essential to support a more uniform graphical context; this will avoid that the percentage of data interpreted by engineers steadily wanes.

5. Technology Co-Development. The European Framework.

More and more, technology development exceeds the expertise of single companies or research institutes and can only proceed by co-development partnerships. This is particularly so for some of the challenges ahead in realizing the integration of structural dynamics design and testing for each of the major disciplinary areas: vibration, acoustics and reliability. Co-development, in particular when it takes place between companies with (partially) competing interests, requires a framework to handle the joint execution of research, to cover the financial risks related to the execution of pre-competitive research, to help with the project management, to protect contributed background and foreground information, and to help with the setting up of exploitation schemes that benefit the partners involved in co-development as well as the potential users of the developed technology.

The European Community, (EC), has progressively developed several programs over the past decade to address this need. The best known are ESPRIT (European Strategic Programme for Research in Information Technology) and BRITE (Basic Research Industrial Technologies). Another program is EUREKA, which is not an EC program, and extends to other European countries. Those programs stimulate cooperation between the European production and Information Technology (IT) industry; they facilitate the involvement of small- and medium-size enterprises. In the composition of projects one strives towards a mix of end users, academic institutes and IT industry. This stands for research which does not aim for academic heights, but is focused on rather more down to earth requirements (or suitable to the engineering community needs). The active involvement of end-users guarantees that the end-focus of the research is the solution of actual problems. The programs are governed by strict project proposal review procedures, as well as project control both from a management and a technical point of view.

The framework that operates within Europe for research and technology development is likely to be extended in the future to a structure that involves both Japan and the United States. Initiatives in such a direction have already been taken.

It is certainly an achievement of companies and research institutes that are active in the area of structural dynamics testing and analysis to have been successful in having several projects approved and completed with good results*.

---

*Note: An overview of some projects is found in the IMAC 9 keynote paper, see *Proceeding of the 9th International Modal Analysis Conference*, Firenze, Italy, 1991. xix-xxv

Conclusions

Solving structural dynamics problems, or better still - designing for optimal structural dynamics performance is a complex task. Various components-noise, vibrations, fatigue, reliability - may interact, requiring an integrated use of several engineering disciplines, modal analysis being just one of them. It is therefore increasingly important to develop synergistic technology that focuses on integrated structural dynamics. It is equally important that systems for modal analysis are designed to fit the requirements of open system integration, where they can interconnect with other engineering analysis in a coherent framework that is receptive to evolution. More and more, such global developments challenge the ability of individual companies and demand cooperation, even co-development. The European research programs have created a framework where users and application developers have worked effectively to solve the more global problems of structural dynamics.

And finally, putting a more integrated approach to work, also implies dealing with organizations and people. To gain acceptance, it is important that a more integrated engineering system does not revolutionize routines and working habits overnight. The capability to comply with actual working procedures and routines that govern in a particular industrial environment or application is of the utmost importance if all expected advantages are to be realized.