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EXAMPLE OF FORMULATION OF AUTONOMOUS ALGORITHMS USED IN PROCEDURE OF MODAL PARAMETER ESTIMATION

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The paper deals with experimental modal analysis used in engineering practice for investigation of structural dynamics of machines, buildings, civil engineering objects, vehicles, air- and spacecrafts as well as ships. The main scope of the research was focused on stabilization diagram processing and modal model consolidation algorithms being parts of the parameter estimation stage of the identification procedure of a considered system. Formulated algorithms of the stabilization diagram processing that use statistical indicators or fuzzy reasoning are presented in the paper. Next, a modal model consolidation algorithm that aims at the determination of the best estimate of each of the identified system poles from a set of its estimates obtained from a series of estimation procedures is described. The algorithm applies statistical measures of the distribution of modal parameters. Finally, examples of application of the formulated algorithms to real data are reported.

Key words: experimental modal analysis, autonomous parameter estimation, stabilization diagram, modal model consolidation

1. Introduction

Experimental modal analysis (Heylen *et al.*, 1997) is a technique of system identification (Norton, 1986) in the case of low frequency vibration analysis of mechanical systems. The analysis is based on the measurement of input/output or output-only characteristics of the investigated system followed by estimation of values of natural frequencies, modal damping coefficients and mode shapes. The applicability of the obtained results is constrained by strict assumption on the modelling dealing with linearity, reciprocity, stationarity and properties of damping forces (Heylen *et al.*, 1997). Very wide practical applications of the technique results from its simplicity, effectiveness, and lack of assumptions concerning structural parameters (mass, damping and stiffness) spatial distribution. Experimental Modal Analysis is used for the identification of structural dynamic properties of machines, vehicles, aircrafts, ships and civil engineering structures. The current and future applicability of experimental modal analysis is discussed in (Van der Auweraer, 2002).

Though experimental modal analysis might be now considered a mature engineering technique, it is important to remark that considerable progress took place during the last 10 years in the methodology of testing and estimation algorithms. First of all, the identification of components of modal models of considered objects that are excited during normal operation, is carried out based on the output-only measurement of operational conditions. This technique is referred to as Operational Modal Analysis (OMA) (Hermans *et al.*, 1999) and it allows one to estimate model parameters for real loading and boundary conditions, which found application in aircraft, high power rotating machinery and civil engineering structures. Next, the technique of real-time modal analysis started to be developed. This technique is crucial for flight flutter testing (Basseville *et al.*, 2001). The accuracy and credibility of the estimation, especially in the case of OMA was considerably improved by implementation of the subspace estimation method that is based on stochastic subspace representation of structural dynamics of a linear system (Basseville *et al.*, 2001). The method proved to be effective also in the case of non-stationary vibration commonly encountered during operation. Another improvement was achieved with the implementation of frequency domain polyreference LSCF algorithm of system poles estimation, which was found to be very fast and reliable (Verboven *et al.*, 2001). The accuracy of estimation might be further improved with the use of optimisation methods (Verboven *et al.*, 2001). The most recently developed OMA was enhanced and improved by introduction of the OMAX method allowing the estimation of modal parameters in the case of both controlled and measurable excitation forces as well as uncontrolled and immeasurable ambient or operational forces acting concurrently (Cauberghe, 2004).

The development of structural testing methodology and both hardware and software used in the structural testing make more and more data being acquired in modal experiments, hence, a large variety of estimation procedures with various parameters is being applied as well. Consequently, engineers face a complex problem of appropriate decision-making that should lead to formulation of unambiguous and credible modal models. The abundance of results makes the process of determination of the final representative modal model very tiresome and time consuming. All of that indicates the necessity of making the modal parameter estimation procedure automatic. Such automation might be obtained in several steps (Lisowski, 2002). First, proper sorting of results and their visualisation should be completed. Then, calculations of the parameter estimation procedure should be fully automated. The last and the most difficult step is to automate the quality assessment of the parameter estimation results. For all the mentioned steps, the main problem to be solved is to automate the decision-making. The decision-making is commonly understood as *selection of alternatives* (Klir and Yuan, 1995). Some objective function that relates alternatives and outcome of their selection is the base of the decision-making. When a proper objective function may be formulated in a deterministic way, the decision-making becomes an optimisation problem. When the deterministic formulation of decision-making is not applicable, the probability of decision outcome is usually being determined statistically and the decision-making is carried out by means of statistical hypotheses (Natke and Cempel, 1997). When the uncertainty of the decision-making is high, then instead of the probability the membership is evaluated and fuzzy reasoning applied (Klir and Yuan, 1995). The alternative approach to the fuzzy sets theory in decision-making in the case of considerable uncertainty is the use of Artificial Neuron Networks or combined neuro-fuzzy techniques which enable introduction of learning or adaptation algorithms for specific data properties into decision-making.

Since the decision-making in experimental modal analysis is still far from comprehensive automation, the current practice is to use the so-called autonomous parameter estimation procedures. Examples of such procedures comprise:

- iterative application of the ERA/DC algorithm (Pappa *et al.*, 1997) supported by selection of estimation parameters generated by the Genetic Algorithm followed by model consolidation (Chhipwadia *et al.*, 1999)

- iterative application of the SMAC algorithm based on modal filtering idea (Mayes and Klenke, 2000) followed by model consolidation (Mayes and Klenke, 2001)

- the statistical frequency domain Maximum Likelihood algorithm consisting in the application of the LSCF (Least Squares Complex Frequency) parameter estimation algorithm followed by the Maximum Likelihood algorithm with an automated pole selection procedure (Verboven *et al.*, 2001)

- a three-step procedure imitating experienced analyst's action in the range of parameter estimation planning, automated pole selection (stabilization diagram processing) and model consolidation (Lisowski, 2002; Lisowski and Kurowski, 2002) with the use of statistical indicators or fuzzy reasoning.

The following description deals with the above mentioned three-step procedure of autonomous parameter estimation.

2. Example of formulation of autonomous algorithms used for decision-making aiding procedure of modal parameter estimation

The considered procedure of autonomous modal parameter estimation consists of four stages:

- planning of parameter estimation
- parameter estimation
- processing of stabilization diagram
- consolidation of the modal model.

The diagram of the formulated procedure is showed in Fig. 1.

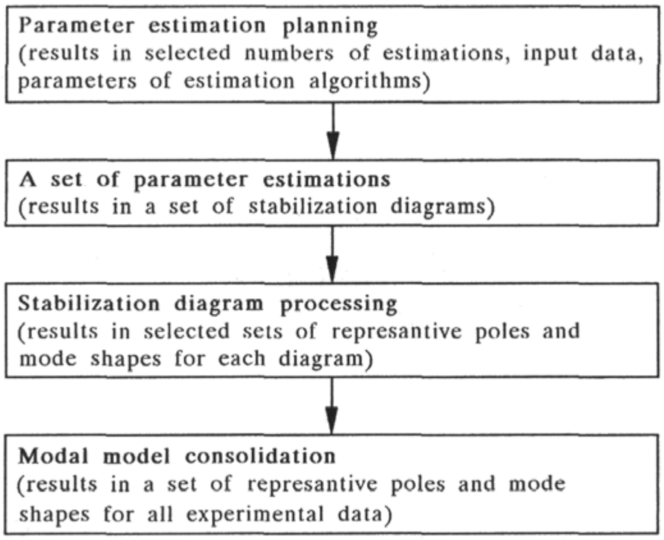

Fig. 1. Diagram of procedure of the autonomous parameter estimation

The requirement of obtaining maximum objectivity of the parameter estimation indicates that not a single estimation but a set of parameter estimation procedures should be performed. Thus the first initial stage consists in planning of a set of such parameter estimation procedures. The planning means in this context the selection of values of parameters of the procedures. In the considered case, results of this stage determine the set of frequency ranges in which parameter estimation is to be performed for a selected reference measuring direction or a set of them. The formulated algorithm uses the dominating minima of a sum of Frequency Response Functions (FRFs) or cross-spectra for the frequency range selection (Lisowski and Kurowski, 2002).

As the second stage, generally, any parameter estimation procedure that produces a stabilization diagram may be used.

The third stage deals with the selection of poles from a stabilization diagram. The stabilization diagram is a commonly used tool in engineering practice which is intended for selection of system physical poles. It presents frequency location of estimated system poles for models of increasing order of the model (Fig. 2).

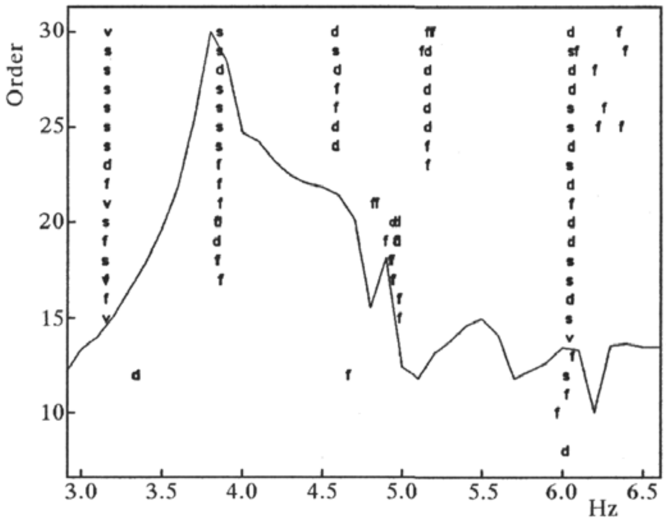

Fig. 2. Example of a stabilization diagram

The use of stabilization diagrams is a result of the lack of effective algorithms for estimating the order of the model of a tested system in the case of real, complex objects. Differences between values of natural frequencies and damping coefficients of the poles belonging to the models of subsequent model orders are calculated and, if small enough, the poles belonging to the model of higher orders are concerned to be stabilised. The calculation proceeds from the lowest to the highest order. Usually, mode shapes or participation factors are also used for assessment of poles stabilization. When a pole is found to be stabilised for a couple of model orders, the pole is considered to be a physical pole, otherwise it is rejected as a spurious (a computational) pole. Stabilization diagrams are usually a subject of complaints of engineers due to necessity of decision-making. Additionally, multiple possibility of selection of poles from the diagrams considerably limits objectivity of the parameter estimation. That is why much detailed research was carried out on the processing of stabilization diagrams. Commonly used algorithms for processing of stabilization diagram are either heuristic or based on the state space model of a dynamic system. Usually an automated heuristic processing of stabilization diagrams consists in decomposition of a diagram into clusters of poles corresponding to a single structural mode and choice of a representative pole for each extracted cluster. The decomposition of a diagram, as a task of classification, is carried out with the use of a statistic procedure (Scionti *et al.*, 2003), fuzzy clustering (Verboven *et al.*, 2004) or fuzzy reasoning (Lisowski and Kurowski, 2002). Also classification algorithms that use artificial neuron nets or Support Vector Machines may be used for that purpose. The model-based methods instead of the physical pole direct selection usually consist in spurious poles rejection with the use of pole-zero cancellation (Scionti *et al.*, 2003), truncation of s balanced representation (Scionti *et al.*, 2003) or backward normalisation (Cauberghe, 2004).

The simplicity and effectiveness of the use of stabilization diagrams made them widely applied in practice. In principle, poles selected from a stabilization diagram by an operator or by a heuristic autonomous algorithm are not proved to be optimally chosen. Introduction of more sophisticated model-based autonomous algorithms like those by Verboven *et al.* (2001) will perhaps allow one in the future to get rid of such an inconsistent tool like the stabilization diagram, and decrease the uncertainty of selection of physical poles related to its use. The necessary condition for that is that the effectiveness of the model-based algorithms is better than the effectiveness of heuristic algorithms, which is generally not the case at the moment.

The last stage of the described procedure deals with the modal model consolidation (Chhipwadia *et al.*, 1999; Lisowski and Kurowski; 2002, Mayes and Klenke, 2001) that consists in the selection of the best mode shape estimates from a set of their available estimates according to an assumed criterion. Benefits of the model consolidation procedure are still underestimated. Generally, such a procedure might be performed sequentially (Pappa *et al.*, 2001) during parameter estimation or when an appropriate set of parameter estimation procedures is completed (Lisowski and Kurowski, 2002; Mayes and Klenke, 2001).

In the following subsections, examples of the stabilization diagram processing and modal model consolidation, which were formulated by the author, will be described.

2.1. Examples of heuristic algorithms for processing of stabilization diagram

The formulation starts from analysis of properties of poles which are visualized on a stabilization diagram. For the purpose of the analysis a set of results of modal testing of three real objects is used, which allowed comparison of 12 stabilization diagrams and 53 lines of poles selected by the formulated algorithm using fuzzy reasoning. The considered clusters of poles correspond to lines of poles, and they are defined in the natural frequency f and modal damping ξ coordinate system ($f - \xi$ plane).

In Fig. 3, a histogram of the length of the extracted lines of poles is presented. It shows that there is no typical length of the line of poles to be found. Thus, the formulated algorithms should work independently of the lengths of pole lines.

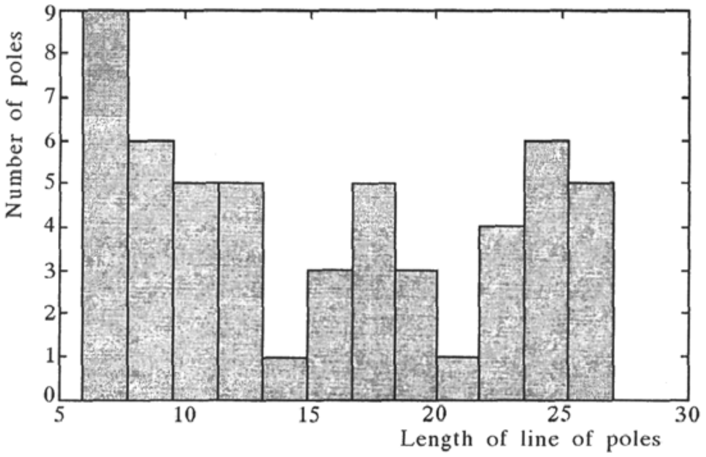

Fig. 3. Histogram of lengths of pole lines

Figure 4 shows a distribution of the natural frequency (*df* – solid line) and modal damping (*dd* – dotted line) for considered 53 lines of poles (clusters). The range of the natural frequency proved to be wider. For approximately half of the lines of poles, $df < 0.4\,\text{Hz}$ and $dd < 0.4\%$, which corresponds to relatively 'narrow' clusters of poles. The comparison of the product *df* times *dd* also shows that a majority of clusters of poles are small (Fig. 5). Thus, the size (understood as an area occupied in the $f - \xi$ plane) of clusters of poles should not considerably influence the performance of the formulated algorithms.

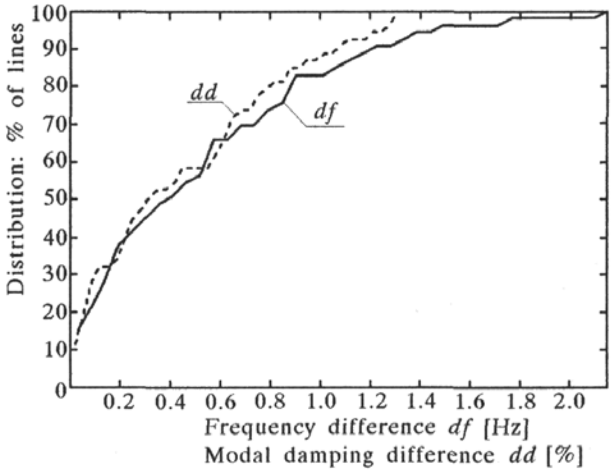

Fig. 4. Distribution of the natural frequency *df* and modal damping *dd* for 53 lines of poles

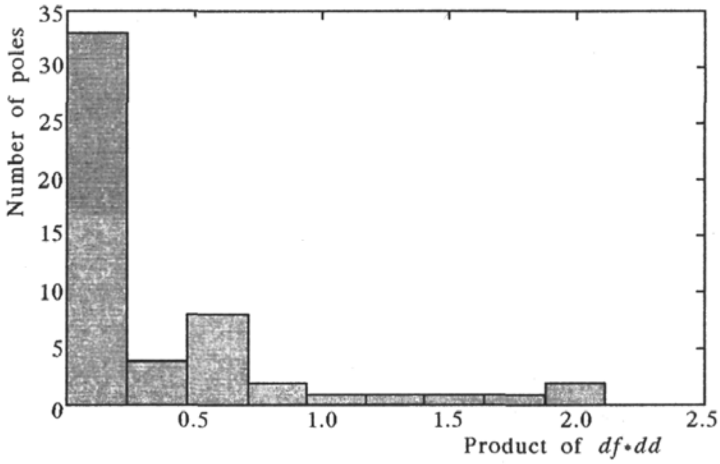

Fig. 5. Histogram of the measure of size of pole clusters

In Fig. 6, a histogram of the position of the pole that is closest to the centre of the cluster of poles in the $f - \xi$ coordinate system is presented. The histogram indicates that generally there is no convergence of lines of poles up to the limit location in the $f - \xi$ coordinate system. Figure 7 shows the change of the natural frequency and modal damping coefficient of three lines of poles corresponding to the same physical pole. These lines were obtained during parameter estimation in three various frequency ranges. The use of a wider frequency range usually leads to worse repeatability of the estimated parameter value for models of various orders (larger cluster of poles in the $f-\xi$ plane). When the fact that usually less accurate estimates of modal parameters are obtained for the lowest model order is taken into consideration, the histogram indicates that a representative pole for a line should be looked for somewhere in the middle of the line and further toward the end, but rather not at the same end of the line of poles.

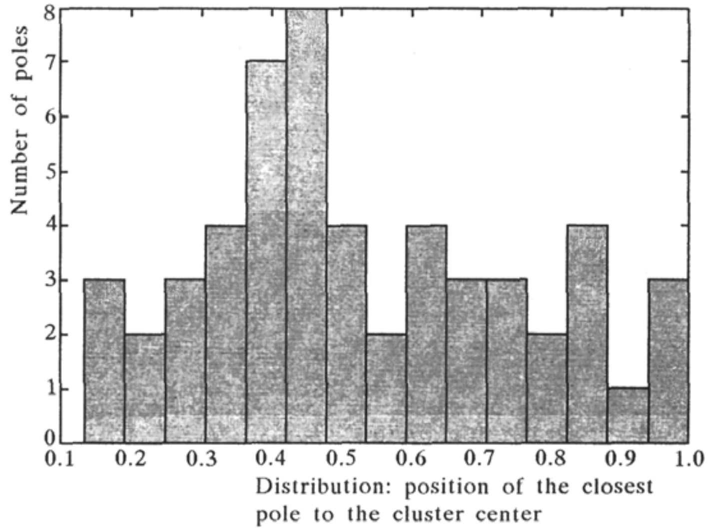

Fig. 6. Position of the pole closest to the centre of the cluster of poles in the $f-\xi$ coordinate system for 53 lines of poles

The presented comparison shows that it is very difficult to formulate a deterministic rule for selection of poles from a stabilization diagram. That is why the author decided to apply a heuristic type of algorithm that should be capable, at least partly, of working similarly to a human operator.

Two algorithms have been formulated.

The first algorithm was originally described by Lisowski and Kurowski (2002). Its block diagram is presented in the left part of Fig. 8.

It uses Mamdani's type fuzzy reasoning (Klir and Yuan, 1995) for the extraction of clusters. The algorithm starts from the determination of the most similar poles out of the model of a higher order to each pole of the model of the current order. For similarity (membership) assessment, like that during formulation of the stabilization diagram, differences in natural frequencies and modal dampings as well as MAC (Heylen *et al.*, 1997) values are used. As a

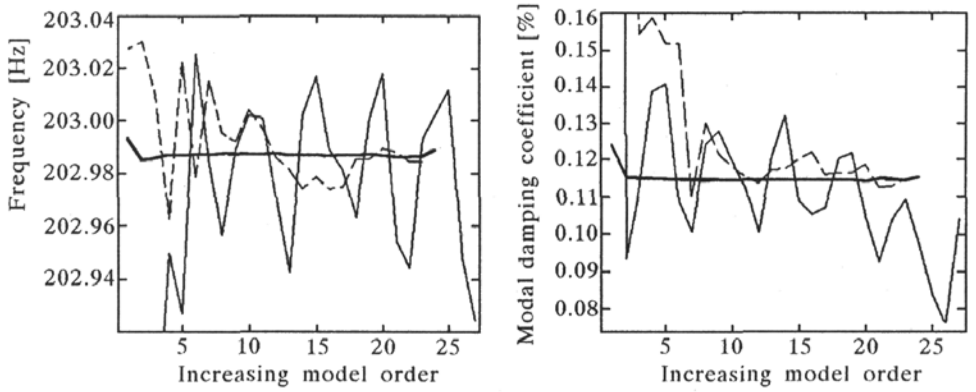

Fig. 7. Variations of the natural frequency and modal damping of three lines of poles corresponding to the same physical pole

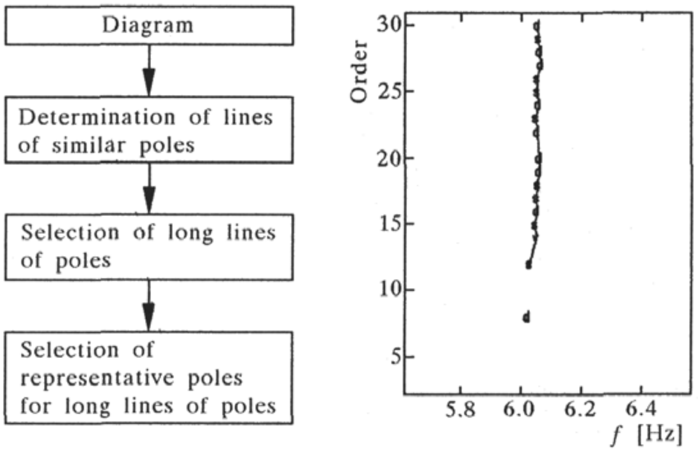

Fig. 8. A block diagram of autonomous processing of a stabilization diagram with fuzzy reasoning

result of the defuzzyfication, similar poles are indicated. The processing of all poles of one diagram leads to the determination of lines of similar poles (an example of such a line is presented in the right part of Fig. 8). While a set of poles belonging to a single line composes a cluster in the coordinate system of natural frequency-modal damping ($f-\xi$ plane), the algorithm allows retaining the information about the sequence of poles in the line of similar poles of each cluster. Additionally, it is capable of using MAC values which are two-argument indicators for clustering.

The second stage of the algorithm results in the selection of the most representative pole from the cluster. Again, fuzzy reasoning is applied. Three indicators are used: distance of each pole from the centre of the cluster in the $f-\xi$ plane, position of each pole in the line of poles corresponding to the cluster and, finally, the quality of stabilization of each pole (property presented in the stabilization diagram by s, v, d, f and o symbols).

The second processing algorithm for stabilization diagrams is of a statistical type. For the clusters extraction it uses only the information about the distance of the natural frequency f_r as well as modal damping ξ_r of various poles to the cluster centre. A block diagram of this algorithm is shown in Fig. 9.

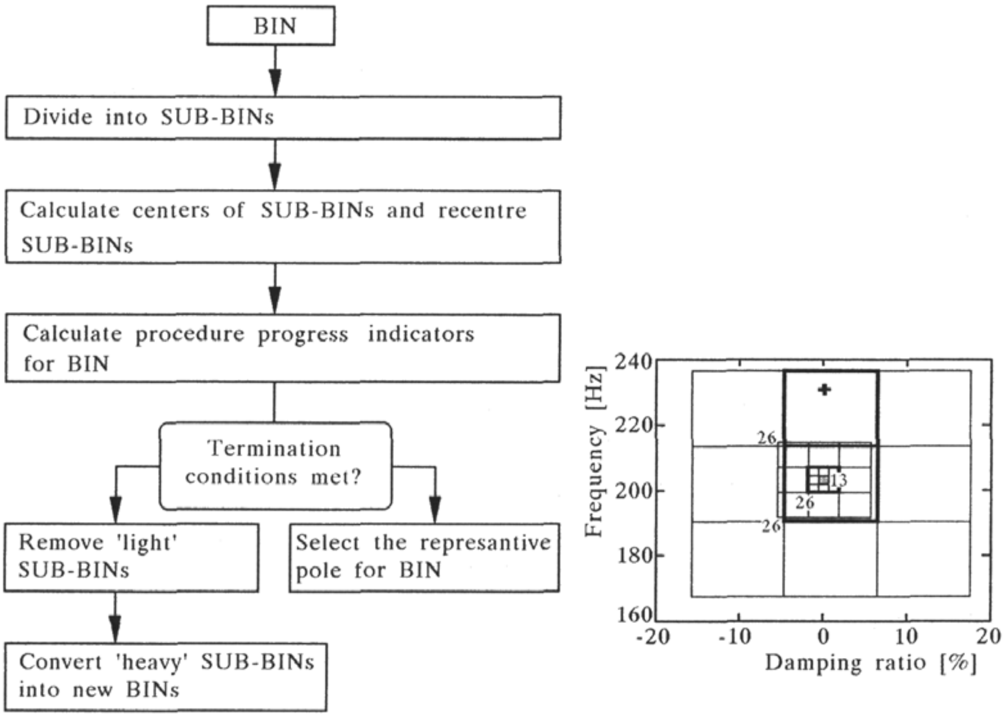

Fig. 9. A block diagram of autonomous processing of the stabilization diagram with statistical indicators

Unlike the similar algorithm described in (Scionti *et al.*, 2003), instead of analysis of the whole natural frequency and modal damping ranges in a single run it is an iterative algorithm. Initially, the whole relevant part of the $f-\xi$ plane is divided into 9 equal areas – bins. Then, each bin is processed the same way. The diagram presented in Fig. 9 corresponds to a single iteration of the algorithm. Each bin is divided again into nine sub-bins. Numbers of poles located in each sub-bin are calculated when this number is higher than the assumed threshold the sub-bin is classified as 'heavy', otherwise its called a 'light' sub-bin. For all poles forming a cluster of poles contained by a sub-bin, a centre in the $f - \xi$ plane is calculated. Each sub-bin is shifted in the $f - \xi$ plane so that the centre of the sub-bin coincides with the centre of the cluster.

The indicators of the algorithm progress are: a new natural frequency range of the sub-bin, new modal damping range of the sub bin, number of 'light' sub-bins, difference in the number of poles in the bin and each sub-bin, difference between an average off-diagonal MAC in the bin and in each sub-bin. The average off-diagonal MAC value is used for the determination whether during current iteration a cluster of poles corresponding to one physical pole or a cluster containing estimates of different physical poles is divided or not. The comparison of calculated values of the progress indicators with their threshold values leads to the determination of the most representative pole from poles located in the considered bin or leads to next iteration carried out for each heavy sub-bin which turns to the bin of the next iteration of the algorithm. The right part of Fig. 9 presents an example of the division and recentring of bins. A bin was divided into nine sub-bins. Only two of them are 'heavy' sub-bins. Seven 'light' bins are rejected. For two remaining 'heavy' bins, another iteration starts. It is presented only for one of them. It was converted to the bin of the next iteration, recentred and divided into nine sub-bins. Only one of the new sub-bins proved to be a 'heavy' one. For such a sub-bin the algorithm will go on. The second part of the algorithm selects the most representative pole from the poles classified to one cluster. The pole that is closest in the $f - \xi$ plane to the centre of the cluster is selected.

2.2. Example of algorithm of modal model consolidation

The author formulated a five-step consolidation procedure composed of data preparation, clustering of modes, determination of each cluster representative modal parameters, followed by the assessment of selected representative modes and the final modal model formulation. The modal model consolidation algorithm aims at the formulation of a single modal model from results of many parameter estimation procedures (Chhipwadia *et al.*, 1999). The representative model is composed of representative mode shapes selected during the described in the previous subsection set of procedures for processing of stabilization diagrams. Application of the model consolidation algorithm shortens time of analysis and additionally increases the objectivity of the formulated modal model. A diagram of the formulated algorithm is presented in Fig. 10.

The first three indicated above steps were described in (Lisowski and Kurowski, 2002) and operate in an automatic way. The data preparation consists of sorting of available mode shapes with respect to the natural frequency and

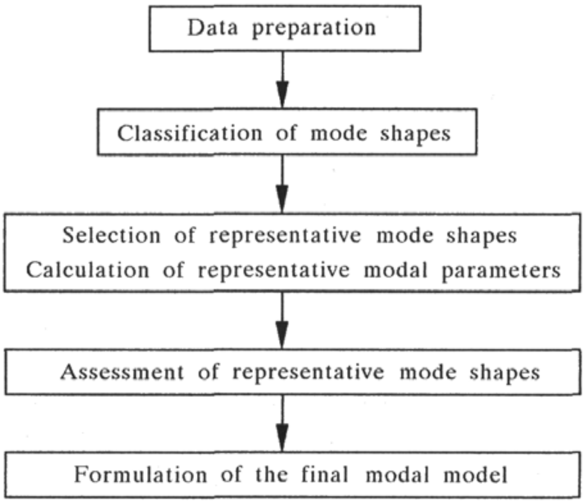

Fig. 10. A block diagram of the formulated modal model consolidation algorithm

calculation of MAC values of each pair of mode shapes of close natural frequencies ($\leqslant 1\,\mathrm{Hz}$). The calculated MAC values are used for the extraction of clusters of similar mode shapes ($\mathrm{MAC} \geqslant 70\%$). During the third step, for each cluster of modes a representative mode shape is selected as the mode shape most similar to modes belonging to the cluster according to MAC. The natural frequency and modal damping of the representative mode shape are calculated as the average of all values of the mode shapes represented by the selected representative ones. Then, the selected representative mode shape and mode shapes represented by it are removed from the cluster. If there is more than one mode shape left in the processed cluster, the procedure of selection of another representative mode shape is started again until no modes are left in the cluster.

The forth stage of the algorithm, still under development, works automatically. A set of assessment indicators is calculated to enable selection of the most representative mode shapes from a set of extracted representative mode shapes. The following basic indicators are calculated:

- number of mode shapes represented by a selected representative mode shape (IPD)
- standard deviation of the natural frequency (SDTF) and modal damping normalized to the average modal damping (SDTT) of modes represented by the selected representative mode shape
- average value of MAC of pairs of modes represented by the selected representative mode shape (MACS).

Also a set of additional indicators is calculated. A majority of them requires making use of modal data during evaluation and also is applicable only in the case of classical modal analysis (contrary to the case of operational modal analysis). Basing on the estimated modal parameters, the mode overcomplexity MOV is calculated (Heylen *et al.*, 1997). With the use of modal data, the following are calculated: a weighted sum of amplitudes of modal characteristics as well as MIF, CMIF (Heylen *et al.*, 1997), correlation SMAC coefficient (Meyes and Klenke, 2000), and a correlation measure of the measurement data reproduction by the SDOF modal characteristic corresponding to the assessed mode shape.

The basic and selected additional assessment indicators are used during the last step of the modal model consolidation algorithm. The threshold values for each of the used indicators are set by the operator according to the purpose of the modal model formulation and specific properties of data. All modes that have indicators grater than the assumed threshold values are selected for the final modal model, which completes the procedure of modal model consolidation.

3. Examples of application of formulated algorithms

As an example of application of the formulated algorithms, the following two case studies are presented in this section:

- comparison of results found from the application of the two formulated algorithms for autonomous processing of stabilization diagrams
- comparison of results of autonomous parameter estimation after model consolidation with the results obtained by an engineer who carried out the testing.

Autonomous processing of stabilization diagrams is presented on an example of results of the Ground Vibration Test (GVT) of the M28 SKYTRUCK airplane. The GVT of the M28 airplane was performed with the use of the Phase Separation Method, i.e. classical modal testing methodology more and more often used for structural testing of aircrafts (Lo *et al.*, 2001). For the excitation, three electrodynamic shakers were used. During the main test, a random excitation was used. Additional tests were performed with a stepped-sine excitation of two levels of the excitation force amplitude and two directions of the 'stepping'. A measuring point net composed of 180 points was used. The main test was carried out as a series of 13 partial experiments. In each partial experiment, 14 triaxial sensors were used. The airplane with fuel was supported on deflated wheels. An additional test for the airframe suspended above the floor was also carried out.

The considered stabilization diagram is shown in Fig. 2. Three considerably distinct lines of poles may be distinguished on the diagram, but two shorter and poorer represented lines of poles are present there, too.

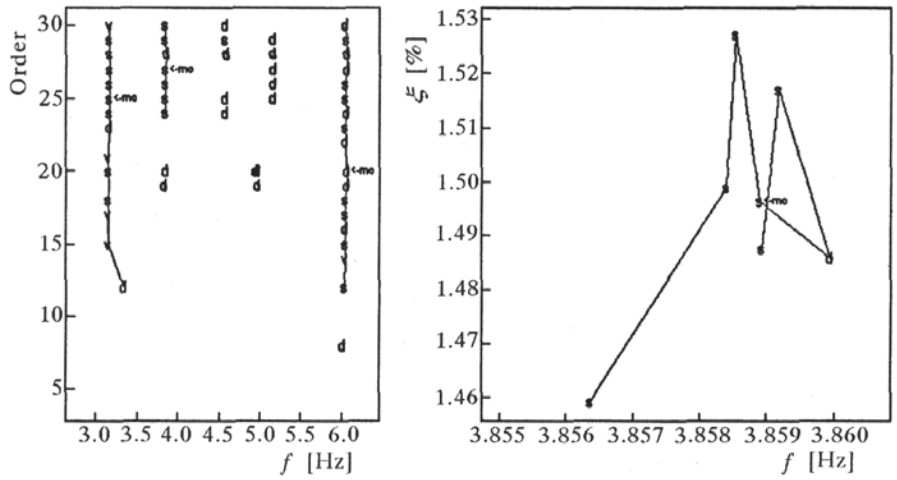

Fig. 11. Example of results of autonomous procedure for processing of the stabilization diagram based on fuzzy reasoning

In Fig. 11, example of results of the application of the processing procedure of the stabilization diagram that uses fuzzy reasoning is presented. Only three lines were selected to be long enough for the selection of representative poles (indicated by $< -mc$) by the considered algorithm. The right part of Fig. 11 shows location of the selected representative pole corresponding to the second line of poles in the $f - \xi$ plane. In Fig. 12, an example of the application of the formulated statistical algorithm for the stabilization diagram processing is presented. The results of the selection of representative poles for the two considered algorithms are listed in Table 1.

Table 1. Results of autonomous processing of the stabilization diagram (natural frequency f_r and modal damping ξ_r)

	Fuzzy reasoning algorithm		Statistical algorithm	
No.	f_r [Hz]	ξ_r [%]	f_r [Hz]	ξ_r [%]
1	3.16	1.32	3.16	1.52
2	3.86	1.50	3.85	1.88
3	6.05	2.08	6.05	2.03

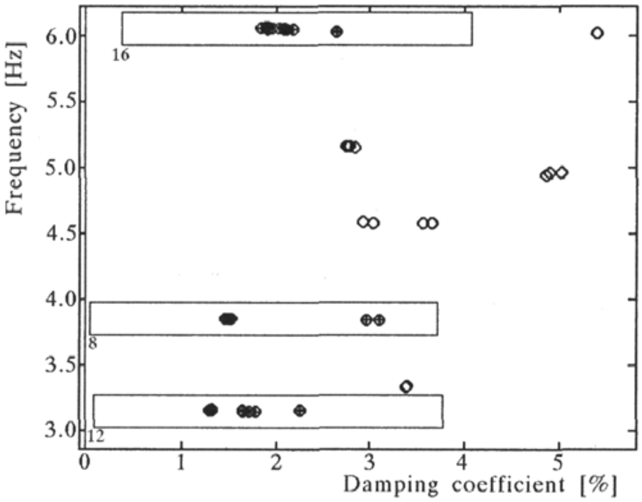

Fig. 12. Example of results of the statistical autonomous processing of the stabilization diagram

Both considered algorithms enabled one to select only three representative poles. The 'short' lines of poles were rejected during processing as too uncertain to represent physical poles. The Table 1 indicates that autonomously selected natural frequencies (in the range of the assumed accuracy of 0.01 Hz) were actually the same or almost the same. The differences between selected representative values of damping were higher due to less accurate identification of damping coefficients. The presented example showed that the application of heuristic algorithms for processing of the stabilization diagram leads to selection of appropriate representative poles for mode shapes that were well represented in the measurement data and, consistently, were distinctly presented on the processed stabilization diagram. For other modes, no result was obtained. This drawback might be made less severe by performing a series of parameter estimation procedures during which various levels of representation of physical poles is usually found. This problem is addressed in the next example.

The second example deals with the three-step autonomous procedure of parameter estimation for GVT data obtained for the M28 SKUTRUCK airplane. The results were compared with those obtained by an expert engineer who carried out the test. Contrary to the previous example, not a single estimation procedure but a set of parameter estimation procedures was carried out. The estimation planning consisted in the selection of reference directions and frequency sub-ranges of subsequent estimation procedures. An example of such selection results for one selected reference direction is shown in Fig. 13.

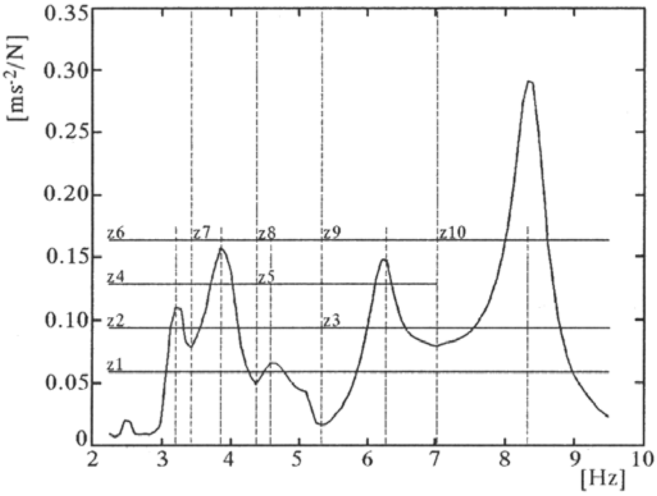

Fig. 13. Example of results of the selection of frequency sub-ranges for parameter estimation procedures

For three available reference measuring directions, 27 estimation procedures were scheduled. Only for eleven stabilization diagrams, the long lines of poles were found with the use of the fuzzy reasoning algorithm. As a result, 36 long lines of poles were found and the representative poles – mode shapes were selected with the use of the fuzzy reasoning algorithm. Then, the modal model consolidation procedure, carried out according to the algorithm described in Section 2.2, led to the formulation of the final modal model composed of five mode shapes (eight modes were present in the considered frequency range). The results of the three-stage procedure are listed in Table 2.

The three remaining mode shapes not consolidated by the autonomous procedure were identified only once, and they were rejected during model consolidation as not repetitively estimated. The application of the modal model consolidation procedure enabled very fast and automatic reduction of the size of the set of parameter estimation results composed of 36 mode shapes down to a set of five mode shapes. The only criterion of the selection used for consolidation was IPD. The second repetitive estimation of the mode was sufficient to consider the mode to be the physical one. All the other assessment indicators were only calculated for the purpose of validation that was to be performed later by the testing engineer. In Table 2, only two of the indicators (SDTF, MACS) are listed. The SDTF indicator showed that the estimation of natural frequencies was very repetitive. For larger clusters of poles, the MACS indicator was lower than for the cluster of only two similar poles. The eighth mode shape, as dominating in the used experimental data, was estimated as much as 16 times.

Table 2. Comparison of results generated by autonomous and interactive procedures of parameter estimation

No.	Interactive estimation		Comparison of mode shapes	Autonomous estimation				
	Natural frequency f_r [Hz]	Modal damping ξ_r [%]	MAC [%]	Natural frequency f_r [Hz]	Modal damping ξ_r [%]	SDTF Δf_r [Hz]	MACS [%]	IPD
1	3.16	1.53	99	3.16	1.34	0.00	100	2
2	3.86	1.48						
3	4.57	3.48						
4	4.65	2.86	90	4.65	2.63	0.02	83	4
5	5.16	2.21	94	5.16	2.35	0.00	99	2
6	6.04	1.74	91	6.05	2.16	0.01	86	4
7	6.16	2.97						
8	8.36	2.15	99	8.31	2.14	0.09	92	16

4. Final conclusions

Computer aided testing tools were introduced into engineering practice many years ago. A majority of such tools is dedicated to specific measurement or analysis. Apart from realisation of a technical procedure of the testing or analysis, they support testing engineers in the interpretation and validation of obtained results. Full automation of these tools is still difficult, most of all due to the necessity of subjective decision-making during the testing or parameter estimation. In this paper, a set of examples of algorithms of autonomous parameter estimation were presented. For the decision-making, they use either comparison of some indicators with assumed threshold values set arbitrarily or with the use of fuzzy reasoning. The presented algorithms are of heuristic type, so they are very sensitive to the assumed threshold values and parameters of the used algorithms. Thus, they require thorough testing and validation before they come into common use. Even after a comprehensive testing, there will always be some uncertainty in the credibility of the obtained results. To lower this uncertainty, the use of always multi-criterion assessment and decision-making in the heuristic autonomous procedures of the parameter estimation is advised.

On the other hand, the application of the presented procedures proved to considerably facilitate the modal model parameter estimation and validation as well as to shorten the time of modal model identification. These, in turn, indicate the necessity of introduction of autonomous procedures for parameter estimation into practice as soon as possible. Thanks to the use of large variety of indicators, their application improves the objectivity of identification results and, thus, their credibility as well. The application of autonomous procedures for parameter estimation should be done with care. It is still not likely that they might make professional testing engineers dispensable in experimental modal analysis. An engineer should be very careful, especially while applying autonomous procedures for parameter estimation during the identification of modal model for the control synthesis purpose or whenever the accuracy of estimation of some modal parameters is crucial.

Finally, it should be noted that the up-to-date autonomous procedures for parameter estimation, to keep pace with the development rate of virtual prototyping tools, require more comprehensive functionality that comprises both the testing and parameter estimation as well as provides more efficient data management and automatic reporting of results.

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Przykłady algorytmów autonomicznych wspomagających estymację parametrów w analizie modalnej

Streszczenie

Praca dotyczy eksperymentalnej analizy modalnej wykorzystywanej w badaniu własności dynamicznych: maszyn, budowli i środków transportu. Opisywane badania dotyczyły przede wszystkim dwu etapów procedury identyfikacji wartości parametrów modalnych: wyboru biegunów z diagramu stabilizacyjnego i konsolidacji modelu modalnego. W pracy opisano dwa algorytmy wyboru biegunów z diagramu stabilizacyjnego wykorzystujące: wybrane statystyczne wskaźniki opisujące własności biegunów lub reguły wnioskowania rozmytego. Następnie opisano sformułowany algorytm konsolidacji modelu modalnego mający na celu wybór najlepszych ze zbioru dostępnych estymat biegunów otrzymanych w wyniku wykonania serii procedur estymacji parametrów modalnych. W sformułowanym algorytmie wykorzystano statystyczne miary rozkładu wartości parametrów modalnych. Opis uzupełniono zestawieniem rezultatów zastosowania sformułowanych algorytmów do wyników badań rzeczywistego obiektu.

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