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COMPARISON OF SIMULTANEOUS AND MULTI-SETUP MEASUREMENT STRATEGIES IN OPERATIONAL MODAL ANALYSIS

Esben Orlowitz[1], *Palle Andersen*[2] *and Anders Brandt*[3]

[1] Ph.D. Student, Department of Technology and Innovation, University of Southern Denmark, eo@iti.sdu.dk

[3] Managing Director, Structural Vibration Solutions, pa@svibs.dk

[3] Associate Professor, Department of Technology and Innovation, University of Southern Denmark, abra@iti.sdu.dk

ABSTRACT

For operational modal analysis (OMA) the multi-setup (or roving sensors) measurements strategy are often applied because the number of wanted measurement DOFs exceeds the number of available sensors. Studies of potential effects of applying the multi-setup strategy in contrast to the optimal simultaneous measurement strategy have, however rarely been reported. Classically, multi-setup datasets are merged together in a post-identification step, known as the patch based approach in experimental modal analysis. Recently, methods for merging the datasets in a pre-identification step has been suggested in the literature, but none of these methods have been compared with simultaneous measurement data. The present paper presents experimental results from an OMA obtained from a measurement consisting of 45 sensors simultaneously measured on a ship in operation. The modal parameters have been estimated for the full dataset, and for three artificially created multi-setup tests based on the full dataset. The first multi-setup test is composed of five datasets that are parallel in time, hence consistency between the datasets is guaranteed. The second test is also parallel in time but with two datasets, and the third test is composed of the same two datasets, but serial in time, hence consistency between the datasets is not guaranteed. For the multi-setup tests merging of the datasets have been done both with pre- and a post-identification methods and the modal parameters are compared with the ones estimated from the simultaneous measurement data. It is shown that using multi-setup tests systematic errors can occur especially in the damping estimates. The tested case where consistency between the datasets could not be guaranteed larger error was observed than when consistency was ensured. In addition, it was found that when mode shapes are of high importance the number of measured DOFs in each dataset should be sufficient larger in order to have a good estimate of the mode shapes.

Keywords: Operational Modal Analysis, Experimental data, Measurement strategy, Damping estimation, Comparison

1. INTRODUCTION

In operational modal analysis (OMA) the multi-setup strategy (or roving strategy as it is normally referred to in classical experiment modal analysis) is often applied to large structures, usually due to the large cost of installing sensors in all DOFs. This measurement strategy is based on selection of a number of reference DOFs that are fixed during the measurements and the remaining available sensors are then roved over the structure until all DOFs have been measured. Some research has been addressing the problem of selecting optimal reference sensor positions for OMA which in general can be compared with selection of reference locations for classical modal testing, see e.g. [1].

When multi-setup data have been acquired during a measurement campaign, data from each setup has to be merged in to one single model of the structure under test. Classically in OMA a post-identification method has been used for this merging where modal parameters are identified from each setup independently and then averaged and collected together [2]. This approach is sometime referred to as the Post Seperate Estimation Re-scaling (PoSER) approach [3]. In EMA this method may be known as the patch-based approach and has been shown to be preferable for inconsistency between the datasets occur [4]. For this reason the PoSER approach seems appropriated for OMA as one often could expect some inconsistency between the setups of a multi-setup measurement on a structure in operation. However, PoSER faces some disadvantages, first it gives a high number of identifications to be conducted (one pr. setup), second the paring and averaging of identified poles can be troublesome and thirdly the merging of mode shapes from each setup can to be troublesome. (LOCAL MODELS FOR EACH SETUP added?)

Recently attention have given to methods that merge the data from a multi-setup test in a pre-identification step, sometimes referred to as Pre Global Estimation Rescaling (PreGER) approaches [2, 3, 5, 6, 7]. This method merge multiple datasets from multi-setup tests before parameter estimation and are thus offering features as: a single estimation process, pairing of modes between setups not needed and global mode shapes are obtained directly, all features that are desirable. (GLOBAL MODEL) The approach of [2] has in general shown its feasibility and to give comparable results as the PoSER approach, however damping estimates were for some modes showing different results [5, 8].

While some comparison between the merging pre- and post to the identification has been done as state above, rarely none attention seems to have been given to their relation to a simultaneously measurement where no merging is necessary. A comparison of multi-setup data processed by the post-identification method and a simultaneously obtained dataset has shown that comparable global modal parameters can be obtained (0.4-30 % difference). However the scatter in especially the damping estimates is considerably larger for the multi-setup data [9].

The present paper present a comparison of the modal parameters obtained when using a simultaneously dataset and using multi-setup data with both the pre-identification merging method from [8] and the post-identification merging method (classical patch based approach). The work is thus an extension to the work previously published in [9] where the post-identification merging method have been applied on the multi-setup data. The two merging methods are referred to as the pre-identification and the post-identification method in the following.

2. METHODS

An OMA test can be decomposed into the following main steps:

- Selection of measurement strategy, roving or simultaneous measurement
- Selection of DOFs to be measured and possibly (if needed) reference DOFs
- Setup of experiment: optimal measurement parameters etc.
- Data acquisition

- Data quality analysis: signal levels, frequency content, stationarity etc.
- Modal parameter estimation

  System identification

  Determination of modal parameters

the present work is focused on the influence of using a measurement strategy with multi-setups or simultaneously measuring all DOFs. For details about the identification method and the merging methods readers are referred to the references.

2.1. Measurement strategies

For OMA there are basically two choices of measurement strategies; simultaneous and multi-setup (roving) measurement. The most direct and optimal way, that minimizes all possible problems with inconsistent data and stationarity issues of both the measured dynamic signals and external loadings, is to measure all wanted DOFs simultaneously. Obviously this demands the number of available sensors and input channels of the data acquisition system to match the number of wanted DOFs.

The multi-setup strategy is based on a limited amount of sensors (and/or input channels) with respect to the number of total DOFs. The strategy is to select a number of reference DOFs, which are fixed for all measurements performed on the structure. The remaining available sensors are then moved between the remaining DOFs in a new setup until all DOFs have been measured. For each setup the measurement time has to be sufficient in order to give good modal parameter estimates. However the datasets from each setup also have to be consistent, as this is a fundamental assumption in the global parameter estimation methods that are used within OMA.

A good practice seems to be to compare at least the RMS levels of the repeated data in order to loosely justify consistency between the sets. Nevertheless each dataset from a multi-setup test will contain less data than the dataset in a simultaneous OMA test and therefore a possibility of larger random error exist.

In the present work multi-setup datasets have been artificially created from a large simultaneous dataset, see Section 3.

2.2. Modal parameter estimation method

For the present work the data-driven Stochastic Subspace Identification (SSI) with the Unweighted Principal Component method [10] has been applied for the estimation of modal parameters. For a detail description of the method the reader is referred to [11] or [10]. For the cases of multi-setup data the used pre-identification method described in [8], and generalized in [12], have been adopted. Here first subspace matrices (or hankel matrices) from each setup are separated into a reference sensor part and a roving sensor part, then the moving part matrices are re-scaled with a common Kalman filter state of one setup and finally merge the together with the reference matrix of with the re-scaling was performed. The outcome is a merged subspace matrix that contains all measured setups, hence the SSI method only has to be performed once. For the post-identification method each setup is analysis though SSI, hence a subspace matrix for each setup is established.

All estimation have been performed through the implementation by Structural Vibration Solutions in the ARTeMIS software [13]. An estimate on the uncertainty is calculated for the natural frequencies and damping ratios based on the stabilized poles for increasing system order up to order 100. Selection of projection channels (reference channels) for the subspace matrices have been selected using the auto setting of ARTeMIS on all datasets for consistency of the analysis. The criteria for stable modes is maximum deviations of $4e-4$ Hz of natural frequencies, 0.1%of 10% of damping ratios and 5% in MAC values between a mode for increasing system order.

Figure 1: The Ro-Lo (Roll-on-Roll-off-Lift-On-Lift-Off) sea vessel from which the used measurement have been acquired.

3. EXPERIMENTAL DATA

The experimental data for the present work originate from a test trial of a 210 meter long Ro-Lo vessel, see Figure 1, equipped with 45 (single-axial) accelerometers (Dytran 3097A3, 500mV/g, IEPE) distributed over 26 measurement points, see Figure 2.

The horizontal (x-y) plane was investigated for torsion modes and therefore all points were measured for vertical vibration (z-direction). The longitudinal vertical (x-z) plane was only investigated for bending modes; hence only points on one side of the deck (point 5 to 15) were measured for horizontal vibrations (y-direction). Longitudinal vibrations (x-direction) were measured at the four points at the deck house (fore) and flume tank (aft), where all three transverse directions were measured.

The data acquisition system used consists of 3x16 channels, 24bit input cards (NI4497), hence all accelerometers were measured simultaneously. For hardware reasons the actual sampling frequency was 1 kHz, and data were down sampled to a sampling frequency of 8 Hz before further processing.

In total 90 minutes was selected for the present work, for which reasonably stationary conditions were found. Stationarity can obviously not be assumed beforehand in the current case and because stationarity is an underlying assumption in estimation of CFs the stationarity of the measured data was investigated. 40 out of the 45 channels passed a hypothesis test (reverse arrangements test) on frame statistics based on RMS levels with a significance level of 0.02 and 100 frames, based on the recommendations in [14]. The frame statistics on RMS levels for one of the rejected channels (#13) are shown in Figure 3, showing shorter periods with divergence from the average level. The rejected channels were visually inspected without finding any crucial issues. Furthermore modal parameter estimation was performed with and without these channels without any significant changes in the modal parameters. The following results are based on all measurement channels.

3.1. Simultaneous test: full data

The full dataset described above is used for comparison with the three multi-setup tests described in the following sections. The full dataset that is simultaneously measured ensures consistency between all measured DOFs, as they have been exposed to the exact same conditions. The full dataset in addition benefit from a large amount of data that can be processed in a single global modal parameter estimation without any merging needed. As stated above the 90 minutes of data were taken within a period of reasonably stationary operation of the ship.

For this dataset the following six references signals was used in the identification procedure, DOF 5(Y,Z), 15(Y,Z), 16(Z) and 26(Z).

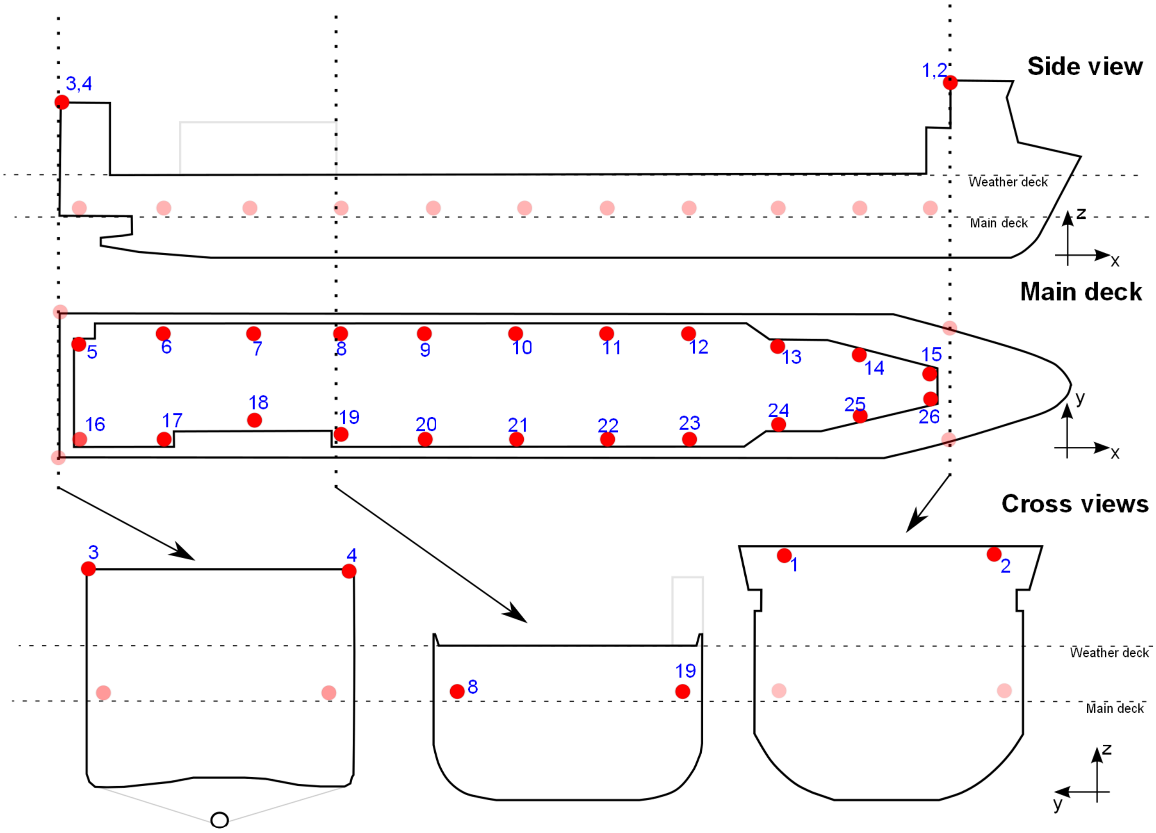


Figure 2: Overview of the ship, including the grid used for the measurements. All measurement DOFs are marked with solid circles

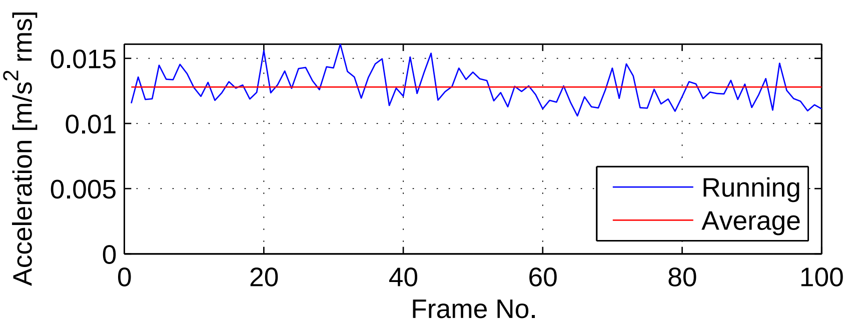


Figure 3: Frame statistics on RMS for channel 13

3.2. Multi-setup test 1: Five datasets, parallel time

A multi-setup test was artificially created from the simultaneous data, assuming 12-channels were available for the test. Three references were selected (DOF 5 (Y,Z) and DOF 16 (Z)) and thus all 45 DOFs were gathered in five setups (moving the 9 non-reference sensors), giving five datasets. In order to guarantee consistency between the datasets in this test they were created using data parallel in time, although this, of course, is unrealistic in practice. In addition this allows the full measurement time (90 minutes) to be available for each dataset. The datasets are composed with DOFs in chronological order, of course always including the three references and obviously equal RMS levels for the reference DOFs are ensured between the datasets.

3.3. Multi-setup test 2: Two datasets, parallel time

Next a multi-setup test is artificially created from the simultaneous data, assuming 26-channels were available because it gives a minimum number of datasets (two). Six references was here selected (DOF 5(Y,Z), 15(Y,Z), 16(Z) and 26(Z)) as more channels were available compared to the test 1, again the two datasets were created parallel in time. The first dataset is composed of DOF 1-9 in all (available) directions and the second of the remaining 10-26 DOFs, in both cases of course including also the references. This multi-setup test benefits from having two datasets compared to the previously described, hence a larger amount of data pr. dataset.

3.4. Multi-setup test 3: Two datasets, serial time

The final multi-setup test is identical to multi-setup test 2 with the exception that the datasets are created in serial time. The first dataset includes the first 45 minutes data for its DOF and the second dataset the last 45 minutes.

No intervening period between the datasets is introduced, although it is practically unrealistic, but in this case it increases the available amount of data. (For the same reason the five datasets case (Multi-setup data set 1) is not created as serial time.).

4. RESULTS

The estimated natural frequencies are presented in Table 1 and the corresponding damping ratios in Table 2. For all tests the five first modes were estimated together with associated estimates of the normalized random error, ε_r =**std**(X)/**mean**(X), where X is a random variable here either natural frequency or damping ratios. The standard deviation **std** is estimated based on all stabilized poles from multiple system orders and for the patch based approach also from the multiple identifications results. For the multi-setup tests estimates from applying both the pre-identification and the post-identification methods are presented in the Tables, name as pre-id and post-id. An representative stabilization diagram is presented in Figure 4. In general the random errors on both frequencies and damping ratios are found smallest for the simultaneous test and largest when the post-identification method is applied on the multi-setup test, especially for the damping ratios.

The auto Modal Assurance Criterion (MAC) matrix for the estimated mode shapes from the simultaneous dataset is shown in Figure 5 with is representative for the results of the other tests - both for the pre-identification and post-identification method. The mode shapes are shown in Figure 6 and are including the first vertical bending, second vertical bending, first horizontal bending, first torsional and third vertical bending mode that correspond to the first five modes of the ship.

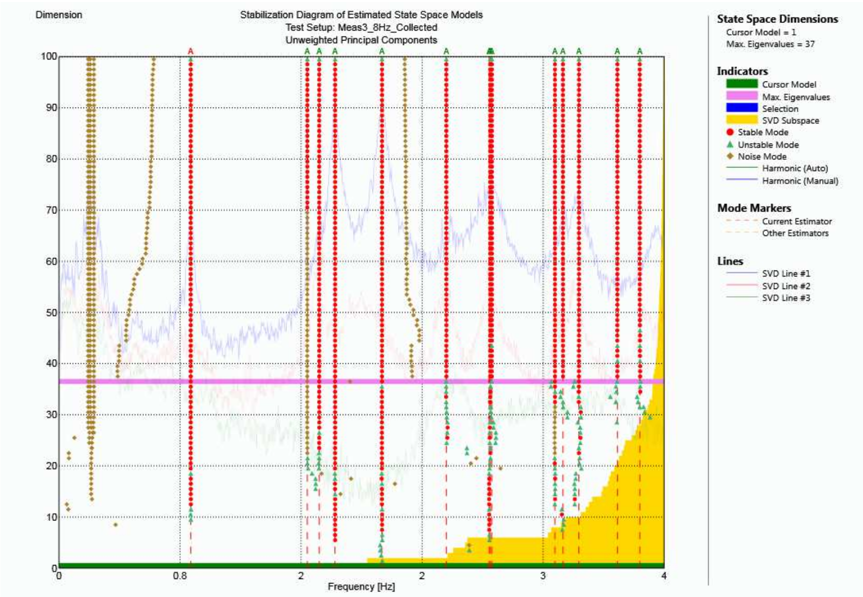


Figure 4: Stabilization diagram for the full simultaneous data set

	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5	
	f_1 [Hz]	ε_r [%]	f_2 [Hz]	ε_r [%]	f_3 [Hz]	ε_r [%]	f_4 [Hz]	ε_r [%]	f_5 [Hz]	ε_r [%]
Simultaneous										
Normal	0.87	0.02	1.72	0.01	1.82	0.01	2.13	0.02	2.56	0.05
Multi-setup 1										
Post-id	0.87	0.12	1.72	0.05	1.83	0.12	2.13	0.06	2.55	0.15
Pre-id	0.87	0.03	1.71	0.01	1.83	0.01	2.13	0.01	2.55	0.00
Multi-setup 2										
Post-id	0.87	0.14	1.71	0.10	1.83	0.11	2.13	0.04	2.55	0.22
Pre-id	0.87	0.04	1.71	0.01	1.83	0.09	2.13	0.02	2.55	0.06
Multi-setup 3										
Post-id	0.87	0.82	1.71	0.84	1.83	0.15	2.13	0.16	2.55	1.18
Pre-id	0.86	0.02	1.70	0.00	1.82	0.00	2.13	0.02	2.53	0.01

Table 1: Estimated natural frequencies, $f_{[]}$, and associated random errors, ε_r, for the Multi-setup test 2 using the pre-identification (pre-id) and the post-identification (post-id) merging methods.

	Mode 1		Mode 2		Mode 3		Mode 4		Mode 5	
	ζ_1 [%]	ε_r [%]	ζ_2 [%]	ε_r [%]	ζ_3 [%]	ε_r [%]	ζ_4 [%]	ε_r [%]	ζ_5 [%]	ε_r [%]
Simultaneous										
Normal	1.85	6.34	1.26	1.00	1.03	1.97	1.15	2.68	1.68	1.00
Multi-setup 1										
Post-id	1.96	11.16	1.06	13.33	1.13	6.52	1.13	6.98	1.36	5.32
Pre-id	1.65	1.24	0.95	0.95	1.06	1.21	1.11	4.82	1.38	0.95
Multi-setup 2										
Post-id	1.69	5.72	0.97	7.54	1.08	3.95	1.13	6.14	1.33	4.04
Pre-id	1.67	2.89	0.96	3.01	1.08	2.56	1.15	6.00	1.35	3.08
Multi-setup 3										
Post-id	1.60	2.06	0.85	9.03	0.98	4.22	1.14	13.05	0.93	9.98
Pre-id	1.88	0.77	1.75	1.01	1.03	1.23	1.24	1.71	3.59	0.39

Table 2: Estimated damping ratios,$\zeta_{[]}$, and associated random errors, ε_r, for the Multi-setup test 2 using the pre-identification (pre-id) and the post-identification (post-id) merging methods.

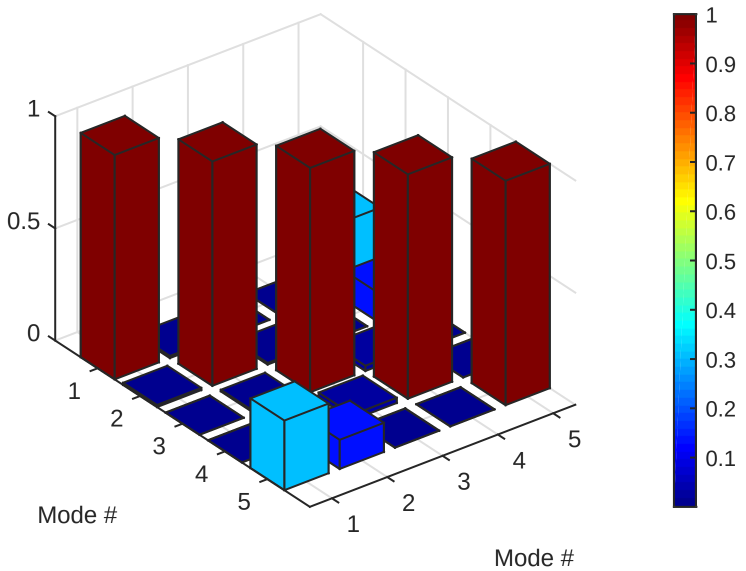
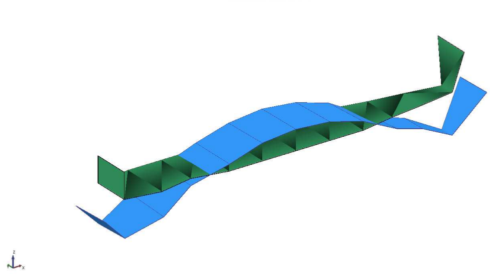
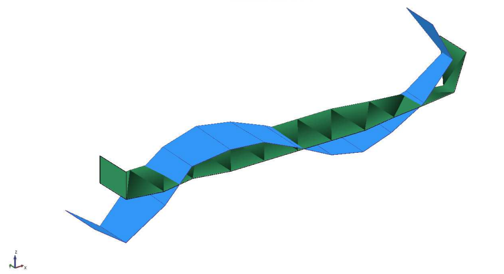


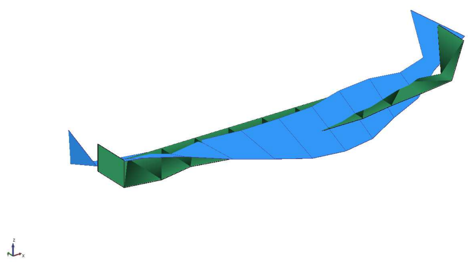
Figure 5: Auto-MAC matrix for the simultaneous dataset.



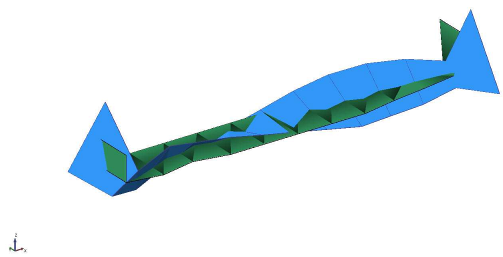
(a) Mode 1: 2-node vertical bending



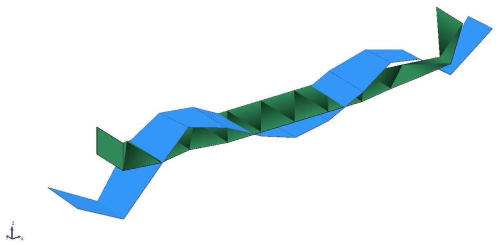
(b) Mode 2: 3-node vertical bending



(c) Mode 3: 2-node horizontal bending



(d) Mode 4: 1-node torsional



(e) Mode 5: 4-node vertical bending

Figure 6: Mode shapes of the five extracted modes, showing maximum deflection and equilibrium.

4.1. Comparison

The estimated natural frequencies, Table 1, and damping rations, Table 2, from the three multi-setup cases is compared with respect to the simultaneous dataset by the relative deviation in Figure 7 and Figure 8. For completeness the deviations are also listed in Table 3 and Table 4 respectively.

From Figure 7 it can be observed that in general the deviations in the natural frequencies are small, however the frequencies from the pre-identification method on Multi-setup 3 stands out with the largest deviations. Of the five modes included in the present work mode 4 is showing a higher frequency than that of the simultaneous dataset, one exception is the pre-identification results of Multi-setup 3, the remaining four modes are all estimated lower for the multi-setup cases. It should be noted that mode 4 is the first (1-node) torsional mode that is containing some horizontal bending motions which is normal for ships with open deck. However as the MAC matrix, see Figure 5, indicate good decoupling of the modes (3 and 4) no obvious reasons for the higher frequency were found.

A similar observation is not seen for the comparison of damping ratios in Figure 8. The deviations of the damping ratios seem randomly higher or lower and in two cases a rather large deviation can be seen when the pre-identification method is used, that is for mode 2 and (especially) mode 5. The case of Multi-setup 3 using the pre-identification method stood out when looking at the frequencies, see Figure 7, does not show a similar tendency for the damping ratios, except for mode 5 shown a deviation of 120 %.

For both natural frequencies and damping ratio it can be observed from Table 3 and Table 4 that the results of Multi-setup 1 and Multi-setup-2 are similar.

In Table 5 the cross-MAC values between the modes from the multi-setup tests and the simultaneous test are compared, that is the diagonal of the cross-MAC matrix. The off-diagonal cross-MAC values are similar to the one in the auto-MAC matrix of the simultaneous test result, see Figure 5. A poor mode shape similarity is observed for the Multi-setup 1 test, where the mode shapes have been composed together from five measurement setups. Also for mode 2 and 5 from the multi-setup 3 test using the pre-identification method poor similarities of the mode shapes are observed.

5. DISCUSSION

A measure of the uncertainties on estimated modal parameters is obviously preferable. For real data no consensus seems to exist on how to give such a measure for the modal parameters in OMA. When a multi-setup strategy is applied in OMA it seems common to display the uncertainties by the scatter between the estimates of the different datasets, see e.g. [15]. When a simultaneous strategy is applied such a measure is not possible. Instead, in the present work a measure of the scatter is obtained based on all stabilized

	Mode 1 [%]	Mode 2 [%]	Mode 3 [%]	Mode 4 [%]	Mode 5 [%]
Multi-setup 1					
Post-id	-0.17	-0.27	0.08	-0.13	-0.22
Pre-id	-0.16	-0.32	0.12	-0.15	-0.35
Multi-setup 2					
Post-id	-0.27	-0.30	0.04	-0.12	-0.33
Pre-id	-0.37	-0.38	0.05	-0.13	-0.48
Multi-setup 3					
Post-id	-0.08	-0.44	0.04	-0.08	-0.33
Pre-id	-0.92	-1.42	-0.16	-0.26	-1.27

Table 3: Relative deviation of natural frequencies from the multi-setup tests with respect to the full simultaneous test.

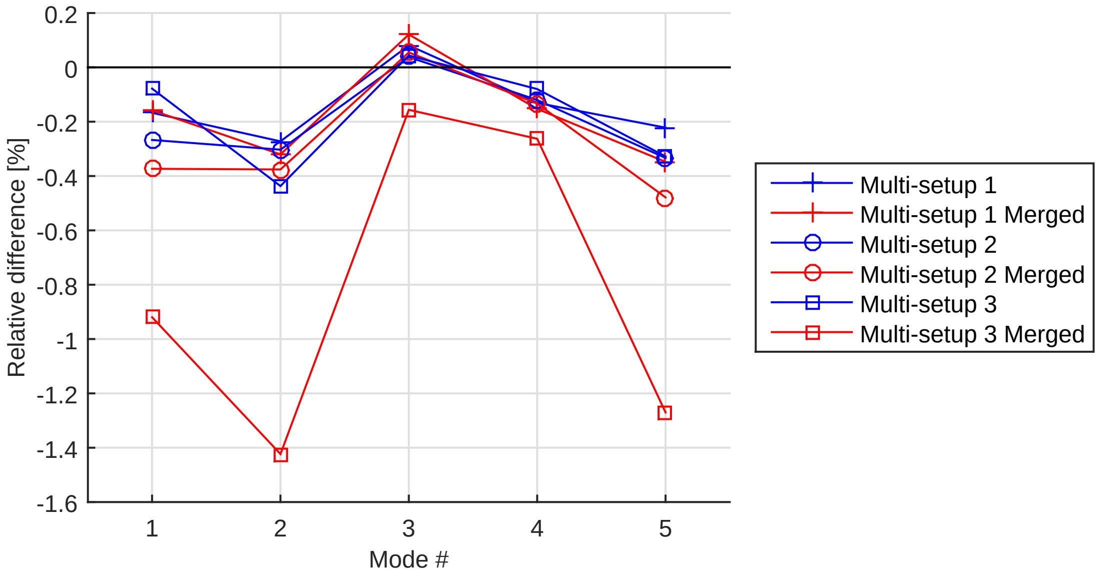


Figure 7: Relative differences in natural frequencies from the multi-setup tests relative to the results from the simultaneous test.

	Mode 1 [%]	Mode 2 [%]	Mode 3 [%]	Mode 4 [%]	Mode 5 [%]
Multi-setup 1					
Post-id	5.72	-15.81	9.52	-2.28	-19.00
Pre-id	-11.03	-24.65	2.69	-3.90	-17.86
Multi-setup 2					
Post-id	-8.69	-23.01	5.00	-1.53	-20.70
Pre-id	-10.08	-24.09	4.74	0.13	-19.57
Multi-setup 3					
Post-id	-13.89	-32.97	-4.85	-0.83	-44.40
Pre-id	1.53	38.31	0.32	8.07	113.27

Table 4: Relative deviation of damping ratios from the multi-setup tests with respect to the full simultaneous test.

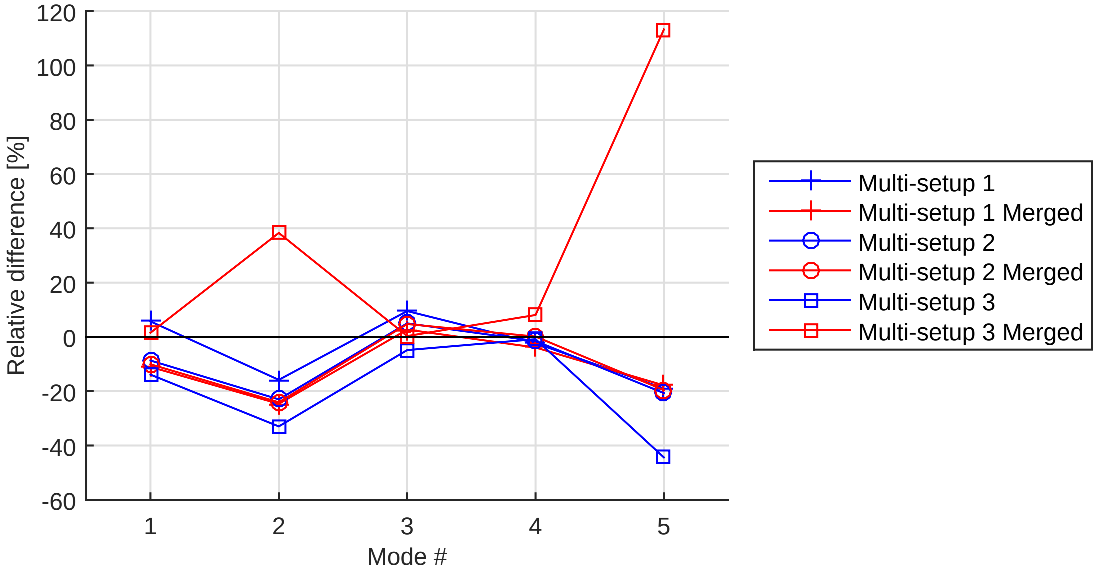


Figure 8: Relative difference in damping ratios from the multi-setup tests with respect to the results of the simultaneous test

	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
Multi-setup 1					
Post-id	0.90	0.88	0.97	0.91	0.89
Pre-id	0.89	0.87	0.97	0.91	0.89
Multi-setup 2					
Post-id	1.00	0.96	1.00	1.00	0.99
Pre-id	1.00	0.96	1.00	1.00	0.99
Multi-setup 3					
Post-id	1.00	0.98	0.97	1.00	0.99
Pre-id	0.98	0.90	0.96	1.00	0.72

Table 5: Comparison of mode shapes from the multi-setup tests with respect to the full simultaneous test by cross-MAC values.

poles from multiple system orders - as observed from a stabilization diagram. Suggestions for other techniques to estimate uncertainties can be found in [16], which is based on first-order perturbations of the system matrices is formulated for a single system order. This formulation have been extended for multi-setup measurement cases [7] and efficient procedures for multi-order uncertainty estimation is suggested in [17].

The most challenging case created in the present work is the Multi-setup 3 that is the only case of datasets from different time periods. This could suggest non- stationary behavior even though it was shown that the present measurements could be assumed stationary. In [18] it has been shown that especially the damping is highly depending on the operation of the ship. Research in parameter estimation of time varying structures is an ongoing topic; see for instance the coming Special Issue on the topic in Volume 47, August 2014, in Mechanical Systems and Signal Processing, but such methods has not been applied on the presented data. Such methods demand some kind of time window to run along the data and the size of such windows would make an influence on the estimates if not selected long enough and thus a classical trade-off between bias (resolution) and random error.

For the results from Multi-setup 3 where the largest (overall) deviation from the simultaneous results is seen it should be noticed that as a consequence of the datasets being serial in measurement time is limited to 45 minutes. That is half the time of the simultaneous dataset and the multi-setup datasets with parallel time. However, it can be observed that the pre-identification method showed small random errors of the estimated natural frequencies and damping ratios which are comparable to (and sometime smaller) errors on the simultaneous dataset. This is a bit disturbing and could indicate that this method is not suitable for the present data as one would expect the error to be smallest for the simultaneous dataset that orients from a longer measurement and is a discovery to be analysis further.

6. CONCLUSIONS

A comparison of natural frequencies and damping ratios from two measurement strategies for operational modal analysis (OMA) have been presented; the multi-setup and simultaneous measurement strategy. For the multi-setup strategy both pre-identification and post-identification merging methods has been applied to collect the multiple datasets. A 90 minute dataset consisting of 45 DOFs measured simultaneously from a ship in operation has been used. The dataset has been used to create three artificial multi-setup tests, as if a multi-setup measurement strategy had been used.

The first multi-setup test was composed of five datasets that are parallel in time, hence consistency between the datasets is guaranteed. The second test was also parallel in time, but with two datasets, and the third test was composed of the same two datasets but serial in time, hence consistency between the datasets is not guaranteed and half the measurement time (45 minute) pr. dataset for the latter case.

The comparison is limited to the first five modes in the frequency range 0.8-2.6 Hz.

As what seems to be a common observation the damping ratio can be a notoriously difficult parameter to consistently estimate from experimental data. In present work it has been shown that the scatter of the estimated damping ratios are larger than the scatter of the natural frequencies and that it is more sensitive to the measurement strategy applied for the acquisition of experimental data.

It has been shown that if the results of the OMA on the simultaneous dataset are treated as the true parameters of the ship using a multi-setup measurement strategy can lead to systematic errors of especially the damping ratios. Deviations up to 113 % have been found in the present work. The multi-setup test with two datasets serial in time showed up to be the most challenging and it should be noted that this should be expected to the case closed to a realistic test.

When studying the artificial datasets that have insured consistency, parallel in time, no different i natural frequency and damping ratios were discovered. However the mode shapes was considerable poor estimated in the case of five datasets (lower number of channels in each set), whereas the case of two datasets (larger number of channels in each set) showed a better estimation of the mode shapes. This holds for both the pre-identification and the post-identification merging methods.

For the present structure, a ship under operation, a clear recommendation for the choice of using the classical post-identification merging (patch based approach) or the pre-identification merging method was not found. Although a sightly advantage point toward the post-identification method which showed a better accordance of natural frequencies and mode shapes for the tested case of two setups serial in time. The case which is the case closed to a realistic ideal multi-setup measurement campaign.

For a structure as a ship that is known to change dynamic characteristics do to different operational conditions it is recommended to perform a simultaneous measurement, especially if the mode shapes is of high importance.

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REFERENCES

[1] Brehm, M., Zabel, V., and Bucher, C. (2013) Optimal reference sensor positions using output-only vibration test data. *Mechanical Systems and Signal Processing*, 41, 196 – 225.

[2] Mevel, L., Basseville, M., Benveniste, A., and Goursat, M. (2002) Merging sensor data from multiple measurement setups for non-stationary subspace-based modal analysis. *Journal of Sound and Vibration*, 249, 719 – 741.

[3] Reynders, E., Magalhes, F., Roeck, G. D., and Cunha, A. (2009) Merging strategies for multi-setup operational modal analysis: Application to the luiz i steel arch bridge. *Proceesings of the International Modal Analysis Conference XXVII, Orlando, Florida*.

[4] Van der Auweraer, H., Leurs, W., Mas, P., and Hermans, L. (2000) Modal parameter estimation from inconsistent data sets. *Proceedings of the 18th International Modal Analysis Conference (IMAC)*.

[5] Döhler, M., Reynders, E., Magalhaes, F., Mevel, L., De Roeck, G., and Cunha, A. (2010) Pre- and post-identification merging for multi-setup oma with covariance-driven ssi. *Proceedings of International Modal analysis XXVIII, Jacksonville, Florida*.

[6] Cara, F. J., Juan, J., and Alarcn, E. (2014) Estimating the modal parameters from multiple measurement setups using a joint state space model. *Mechanical Systems and Signal Processing*, 43, 171 – 191.

[7] Döhler, M., Lam, X.-B., and Mevel, L. (2013) Uncertainty quantification for modal parameters from stochastic subspace identification on multi-setup measurements. *Mechanical Systems and Signal Processing*, 36, 562 – 581.

[8] Döhler, M., Andersen, P., and Mevel, L. (2010) Data merging for multi-setup operational modal analysis with data-driven ssi. *Proceedings of the IMAC-XXVIII, Jacksonville, Florida, USA*.

[9] Orlowitz, E. and Brandt, A. (2014) Effects of simultaneous versus roving sensors measurement in operational modal analysis. *Proceedings of Conference on Noise and Vibration Engineering, Leuven*.

[10] Overschee, P. and Moor, B. (1996) *Subspace Identification For Linear systems*. KLUWER ACADEMIC PUBLISHERS.

[11] Peeters, B. and De Roeck, G. (1999) Reference-based stochastic subspace identification for output-only modal analysis. *Mechanical Systems and Signal Processing*, 13, 855–878.

[12] Döhler, M. and Mevel, L. (2012) Modular subspace-based system identification from multi-setup measurements. *IEEE TRANSACTIONS ON AUTOMATIC CONTROL*, 57, 2951–2956.

[13] *ARTeMIS Modal 3.5 [Computer software]. Issued by Structural Vibration Solutions A/S. NOVI Science Park, Niels Jernes Vej 10, DK 9220 Aalborg East, Denmark*.

[14] Himelblau, H., Wise, J. W., Piersol, A. G., and Grundvig, M. R. (1994) *Handbook for Dynamic Data Acquisition and Analysis - IES Recommended Practices 012.1*. Institute of Environmental Sciences.

[15] Qin, S., Reynders, E., He, L., Bui, T., and De Roeck, G. (2014) Effects of initial conditions in operational modal analysis. *Structural Control and Health Monitoring*, 21, 557–573.

[16] Reynders, E., Pintelon, R., and De Roeck, G. (2008) Uncertainty bounds on modal parameters obtained from stochastic subspace identification. *Mechanical Systems and Signal Processing*, 22, 948–969.

[17] Dhler, M. and Mevel, L. (2013) Efficient multi-order uncertainty computation for stochastic subspace identification. *Mechanical Systems and Signal Processing*, 38, 346 – 366.

[18] Orlowitz, E. and Brandt, A. (2014) Operational modal analysis for dynamic characterization of a ro-lo ship. *Journal of Ship Research*, 58.