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DAMAGE LOCATION DETECTION IN COMPLEX MECHANICAL ASSEMBLIES

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Abstract: *Structural damage occurs in any system, mechanical or not, even in living things. Mechanical damage means the appearance of irreversible changes in structural characteristics. Methods for structural monitoring are ways to estimate any changes in structural strength. Damage detection techniques give warnings at the right moment on duty before failure of the structure create more damages. After years of research damage detection techniques evolve to a higher level for localization of damage in complex assemblies. Finding the precise location of the damaged area helps in taking the first action to avoid catastrophic failure to the structure. This study presents an improved DLAC method for damage localization technique applied to a conceptual mechatronic system for laparoscopic surgery.*
Key words: *Damage detection, damage location, Stewart platform, robotics.*

1. INTRODUCTION

Damage when appearing may cause losing sections or parts, excessive deflection, buckling failure, cracks, changes in vibration eigenvalues and eigenmodes, loss of capabilities to support loads, changes in durability and shortening of the service life of products.

Structural Health Monitoring (SHM) is applied today to structures that require significant costs, where human safety is a priority, or for structures difficult to inspect, like satellites [1-2], bridges [3-6], very tall buildings [7-8], aircrafts [9-10], wind turbine systems [11], and even for robots [12]. SHM is a good practice to assess the general state of structural integrity during service.

Damage detection involves today also methods to estimate damage location, damage size, or other additional information about the damaged area.

For complex assemblies is not quite easy to estimate damage location after damage appear and detected. Processing a large number of matrices of the mathematical system, correlation of all data, eigenmodes right identification and ordering, understanding of meanings of parameters involved, assess of energetical characteristics, are only a few tasks that should be made.

The amount of information that could be extracted from dynamic systems is not stopped here. Using modern sensor systems with more capabilities to extract, interpret and show the measured data, new devices are on the sketch in design.

The following research shows the results of a study that presents some of the fundamental principles of monitoring structures, detecting damages, and locating them in complex mechanical assemblies [13].

The monitoring method used in this research is based on determining the fundamental frequencies of a system [14] and monitoring their variation. [15].

2. METHODOLOGY

The main characteristics of the study of the dynamic behavior of a system are eigenvalues and eigenvectors of the structure. These has a direct influence on the dynamic behavior in the service, as well as vice versa.

Knowledge of eigenvalues and eigenvectors allows:

- Assessment of the slenderness of the structure, which is the ratio between mass and rigidity;
- Knowledge of the fundamental frequency;
- The calculation of the system response to a transient load can be done by the modal method (decomposition of the signal into a sum of harmonics, the calculation therefore requires the knowledge of resonant frequencies);
- Identification of systems according to experimental measurements;
- Correlation of mathematical models with experimental model [14];
- Damage detection [15-20];
- Damage localization [21-22].

Damage detection is based on changes in the modal parameters: frequency, damping, eigenmodes, modal distortion energy, dynamic flexibility, anti-resonance, etc.

The easiest parameter to monitor is the resonant frequency due to the type of sensors to be used - accelerometers. These sensors are simple, inexpensive, easy to understand and set up, easy to use for recording and processing signals, etc.

Damage Local Assurance Criterion (DLAC) proposed by Messina [23] was used in this paper to assess the position of the damage. The method uses the evaluation of changes in natural frequencies based on the following equation:

$$DLAC(i) = \frac{\left|\Delta\omega_E^T \Delta\omega_A(i)\right|^2}{\Delta\omega_E^T \Delta\omega_E \left(\Delta\omega_A^T(i)\Delta\omega_A(i)\right)} \quad (1)$$

where A and E are obtained from the analytical and experimental model, respectively, which must be compared, and $\Delta\omega_x$ is the variation in the resonant frequencies.

The DLAC method has been improved by using scaling factors that turn the value criterion into a probabilistic one, called a probability DLAC index for easier evaluation [24].

3. CASE STUDY

The model used for this research is a hexapod robot. The damages could appear in many locations but the most probably at the actuators. Figure 1 shows the robot and damaged locations used for assessment. Configuration of the Hexapod system is a Gough-Stewart platform with reference definitions showed in figure 2.

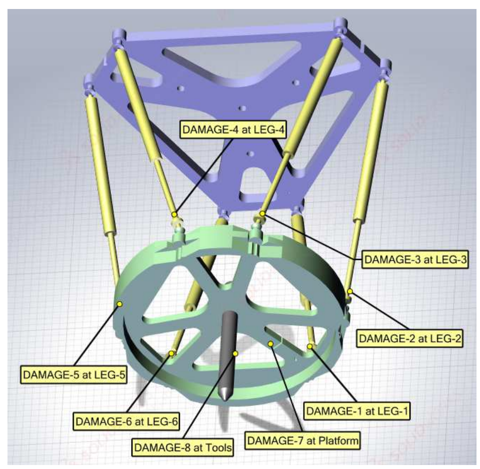
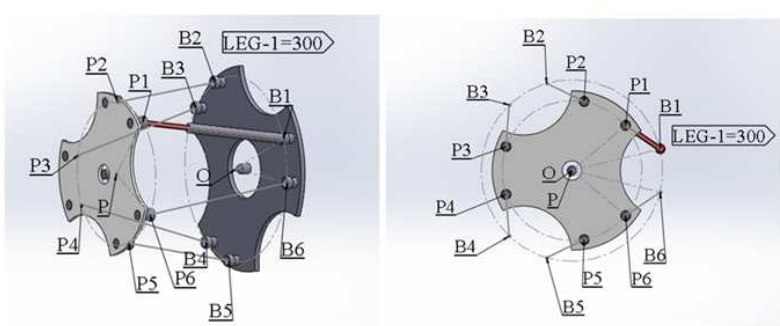


Fig. 1. Hexapod robot and damage locations.



(a) Isometric view (b) Reference points distribution

Fig. 2. Hexapod configuration.

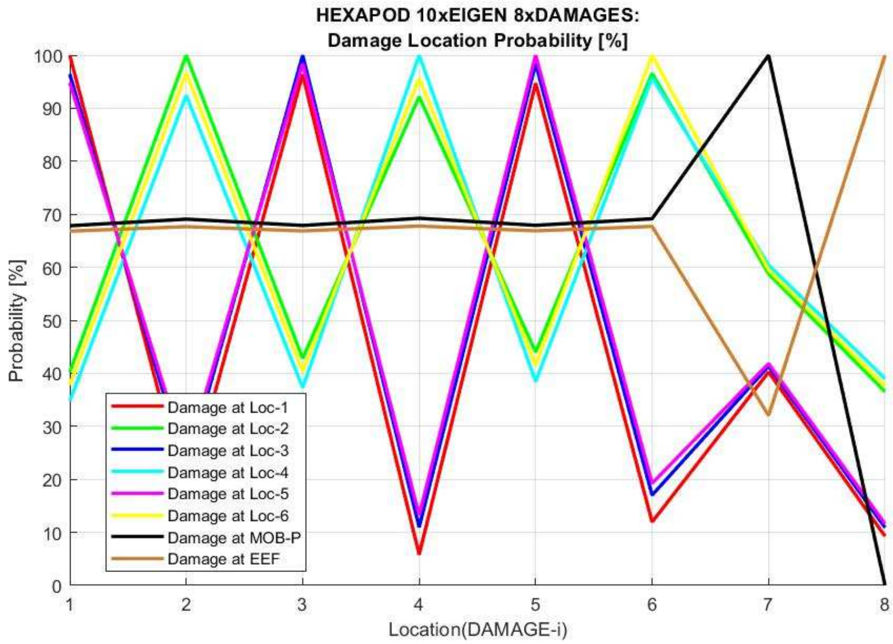


Fig. 3. DLAC probability index assessment.

The detailed CAD model and simulations was made using professional software Solidworks.

Ideally, this kind of damage localization should be made using a correlation study between a virtual and an experimental model. Because the experimental model is not built yet, in this paper, DLAC criterion is evaluated based on two sets of simulation results: first set for initial, no damaged structure, and the second set is for the structure damaged at specific locations. Examples of damage introduced in model are presented in figure-4 and in figure-5.

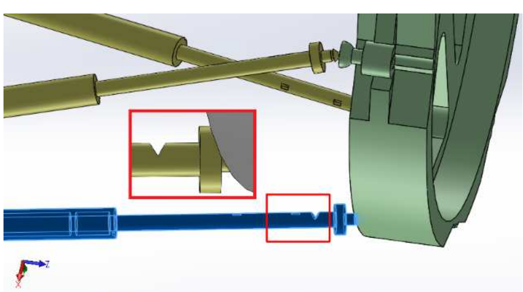


Fig. 4. The damage introduced in model at location-1 for leg-1. Similar for each leg of Stewart platform.

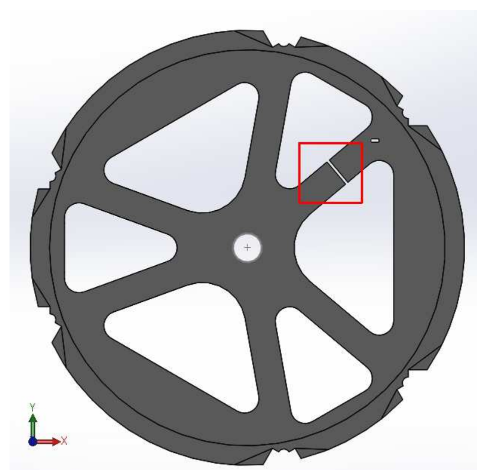


Fig. 5. The damage at platform

For the simulation model, the damages were intentionally introduced at specific locations. In this research was used 10 eigenmodes and 8 damaged areas. The DLAC criterion became more complex when is used many numbers of eigenmodes and many damaged areas.

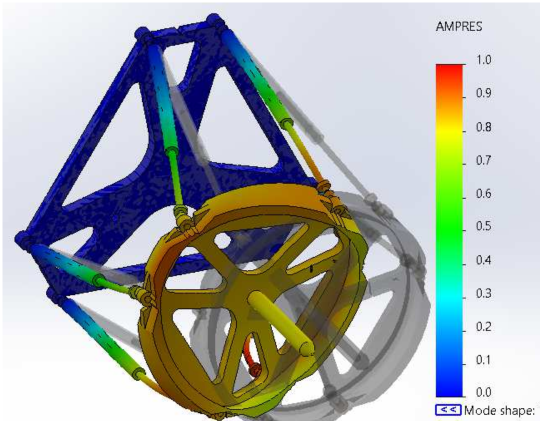


Fig. 6. Eigenmode at fundamental resonance frequency.

Figure 3 shows the results from the assessment of the DLAC probability index. During monitoring, changes may occur in the order of the eigenmodes from the undamaged to the damaged model. Identifying vibration modes is an important issue in research on frequency response analysis. Incorrect identification and correlation lead to incorrect localization of structural damages.

Figure 6 shows the fundamental resonance eigenmode for undamaged model.

Simulations constraints doesn't take into consideration any movement between parts. All contacts are considered bonded and any motor is blocked.

The shift in frequencies is presented in Table 1 only for undamaged model, with damages at Leg-1 or Leg-2.

Table 1

Frequency shift table for damages at location 1 and 2.

Eigen mode	Resonance Frequencies [Hz]		
	Undamaged	Damage at Location 1	Damage at Location 2
1	54.384	53.71938	53.84174
2	54.589	54.47858	54.34298
3	96.136	95.79068	95.77724
4	114.42	114.3582	114.3559
5	114.55	114.4752	114.478
6	142.25	142.0083	142.0008
7	203.06	202.8752	202.8519
8	203.23	203.0025	203.0323
9	204.87	204.8229	204.8203
10	210.34	210.2732	210.3183

4. CONCLUSIONS

The probability index of DLAC criterion shows the maximum value exactly where the damage was introduced in each model. This is possible when exist only one damaged area. In case of simultaneous existence of several damages, the DLAC method is no longer effective, being necessary to corroborate with other criteria for a correct evaluation.

By increasing the number of masterpoints (measurement points) that can be monitored, it is possible to obtain better results for localization of damages. But using large number of master nodes and eigenmodes can lead to incorrectly assessing the location of the damage.

The method can be used on any set, even the most complex mechanical structures. But the number of measuring points and the identified modes must be chosen to be able to obtain clear information about the location of a damage in the case of complex assemblies.

Finally, an intelligent damage monitoring can be done by implementing MEMS sensors attached to the robot. The raw data detected by the acceleration sensor is transferred for evaluation and transmitted to the Main Command and Control Unit.

Damage localization technique advantages:

- Damage localization is a reliable technique for monitoring of mechanical structures during evaluation, testing and service;
- DLAC criterion has a better evaluation in terms of probability;
- The main advantage of the method is that is useful also for large assemblies;
- When the numerical model is continuous and linear, the DLAC correlation procedure is a robustly method;
- Because of the non-linearity of the FRF of the hexapod in vibration modes and at frequency shift, method reveal influence of the vibration mode shapes over displacements at each master node;
- Method results are showed into a simple but concise graphic representation based on probability using DLAC rescaling.

DLAC criteria give errors in localization in case of small damages (< 2% changes in local stiffness) because of small changes in frequencies and of the influence of the participation factor of each part at global stiffness and of the vibration modes at each probe location.

The aim of this research was to develop methods for new advanced design of a surgical robots. Using robots in medical care involve many aspects for safety [25].

The complete solution of the simulations was made based on the MATLAB program [26], SOLIDWORKS Educational [27] and with special programming routines developed by the user [28].

5. ACKNOWLEDGMENT

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6. REFERENCES

[1] Kabashima, S., Ozaki, T., and Takeda, N., *Damage detection of satellite structures by optical fiber with small diameter*", Smart Structures and Integrated System, 2000, vol. 3985, pp. 343–351. doi:10.1117/12.388837.

[2] Qi, L, Yan, R., Sun, L., (2017), *A Study of Structural Damage Detection for Spacecraft In-Orbit Based on Acoustic Sensor Array*, International Journal of Aerospace and Mechanical Engineering, 1307-6892.

[3] Casas J.R., Moughty J.J., (2017), *Bridge Damage Detection Based on Vibration Data: Past and New Developments,* Frontiers in Built Environment, Vol.3, ISSN=2297-3362, DOI=10.3389/fbuil.2017.00004

[4] Döhler, M.,Hille, F., Mevel, L. & Rücker, W., (2014), *Structural health monitoring with statistical methods during progressive damage test of S101 Bridge*, Engineering Structures Press, vol.69, pp183–193.

[5] Lakshmi, K., Keerthivas, M., (2021), *Damage diagnosis of high-rise buildings under variable ambient conditions using subdomain approach,* Inverse Problems in Science and Engineering, 29:13, 2579-2610, DOI: 10.1080/17415977.2021.1941922

[6] Bukhsh, Z.A., Jansen, N. & Saeed, A., (2021), *Damage detection using in-domain and cross-domain transfer learning*. Neural Comput & Applic, vol. 33, 16921–16936 https://doi.org/10.1007/s00521-021-06279-x

[7] Zhili Hea, et all, (2022), *Automatic damage detection using anchor-free method and unmanned surface vessel*, Automation in Construction Jr., Volume 133, 104017

[8] Chiou, D.-J. et al. (2011) "Applications of Hilbert-Huang transform to structural damage detection", Structural Engineering and Mechanics, Volume 39 Issue 1 / Pages.1-20, 1225-4568(pISSN) / 1598-6217(eISSN) doi: 10.12989/SEM.2011.39.1.001.

[9] Ohad Gur, (2020), *Aircraft Damage Detection Using Metamodeling techniques*, Israel Aerospace Industries Papers, Esteco Journal

[10] Chady, T.; Okarma, K.; Mikolajczyk, R.; Dziendzikowski, M.; Synaszko, P.; Dragan, K., (2021), *Extended Damage Detection and Identification in Aircraft Structure Based on Multifrequency Eddy Current Method and Mutual Image Similarity Assessment*, Materials Journal, vol.14, pp.4452., https://doi.org/10.3390/ma14164452

[11] Ulriksen, M.D., Tcherniak, D., Kirkegaard, P.H., Damkilde, L., (2016), *Operational modal analysis and wavelet transformation for damage identification in wind turbine blades*, Structural Health Monitoring, vol. 4, pp.381-388.

[12] Bartlett, M.D., Markvicka, E.J., Tutika, R., Majidi, C., (2019), *Soft-matter damage detection systems for electronics and structures*, Proc.SPIE10971, Nondestructive Characterization and Monitoring of Advanced Materials, Aerospace, Civil Infrastructure, and Transportation XIII, https://doi.org/10.1117/12.2514311

[13] Dragne, C., Chiroiu, V., Iliescu, M., Todirite, I., (2022), *Damage detection and smart warning for eventual structure failures in mechatronic systems*, IEEE World Conference on Applied Intelligence and Computing AIC2022.

[14] Ewins, D.J., (1985), *Modal Testing: Theory and Practice*, Wiley, New York.
[15] Doebling, S., Farrar, C., and Prime, M., (1998), *A summary review of vibration-based damage identification methods*, Shock and Vibration Digest, 30, p. 91-105.
[16] Friswell, M. I., and Mottershead, J. E., *Finite Element Model Updating in Structure Dynamics*, Netherlands, Kluwer Academic Publishers, (1995).
[17] Casas Joan R., Moughty J.J., (2017), *Bridge Damage Detection Based on Vibration Data: Past and New Developments*, Frontiers in Built Environment, vol3, DOI=10.3389/fbuil.2017.00004.
[18] K. He and W.D. Zhu, (2011), *Structural Damage Detection Using Changes in Natural Frequencies: Theory and Applications*, J. Phys.: Conf. Ser. 305 012054.
[19] Peng, C et all, (2015), *Damage Detection and Quantification Using Transmissibility Coherence Analysis*, Shock and Vibration Journal, https://doi.org/10.1155/2015/290714.
[20] Mohan, V., Parivallal, S., Kesavan, K., Arunsundaram, B., Farvaze, A.K., Ravisankar, K., (2014), *Studies on Damage Detection Using Frequency Change Correlation Ap-proach for Health Assessment*, Procedia Engineering, Volume 86, Pages 503-510, ISSN 1877-7058, https://doi.org/10.1016/j.proeng.2014.11.074
[21] Yang, Zhichun & Wang, Le., (2010), *Structural Damage Detection by Changes in Natural Frequencies*, Journal of Intelligent Material Systems and Structures - J INTEL MAT SYST STRUCT. 21. 309-319. 10.1177/1045389X09350332.
[22] Yan, A., Kerschen, G., De Boe, P., and Golinval, J., *Structural damage diagnosis under varying environmental conditions part I: a linear analysis*. Mech. Syst. Signal Process. 19, 847–864. doi:10.1016/j.ymssp.2004.12.002, (2005).
[23] Messina, A., Jones, I., and Williams, E., (1992), *Damage detection and localization using natural frequency changes*, Proceedings of the 1st Conference on Identification, Cambridge, England, UK, 1, p. 67-76.
[24] Dragne, C., *Stewart Platform – Damage Detection Based on Frequency Shift*, SISOM and Session of the Commission of Acoustics, Bucharest 23 Oct. 2021.
[25] Ferrarese, Alessia et al., *Malfunctions of robotic system in surgery: role and responsibility of surgeon in legal point of view*, Open medicine (Warsaw, Poland) vol. 11,1 286-291. 2 Aug. 2016, doi:10.1515/med-2016-0055.
[26] https://www.mathworks.com/help/ , accessed on 2022
[27] https://www.solidworks.com/ , accessed on 2022
[28] https://grabcad.com/ciprian.dragne/ , accessed on 2022.

Detecția și localizarea deteriorărilor în ansamblele mecanice complexe

Deteriorări structurale apar în orice sistem mecanic și nu numai, chiar și la viețuitoare. Deteriorarea mecanică înseamnă apariția unor modificări ireversibile ale caracteristicilor structurale. Metodele de monitorizare structurală sunt modalități de estimare a unor modificări în structura de rezistență. Tehnicile de detectare a defectelor oferă avertismente la momentul potrivit în timpul executării sarcinilor înainte ca defecțiunea să creeze și mai multe daune. După ani de cercetare, tehnicile de detectare a daunelor au evoluat la un nivel superior pentru localizarea acestora în ansambluri complexe. Găsirea locației precise a zonei deteriorate ajută la luarea primelor măsuri pentru a evita defectarea catastrofală a structurii. Acest studiu prezintă o metodă DLAC îmbunătățită pentru tehnica de localizare a defectelor apărute într-un sistem mecatronic destinat chirurgiei laparoscopice.

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