Information-based sensor placement optimization for BWB aircraft

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Abstract: Information approach to optimal sensor placement is called to assign accelerometers as effective indicators of flexible vibrations in a next-generation large passenger blended-wing-body aircraft (BWB). This step presents a crucial prerequisite for the subsequent design of active dampers, either separately or as a part of integrated flight controls / active damping systems. Results of the classical Fisher information matrix algorithm (FIM) are presented first. Their interpretation in terms of spillover of higher modes leads to a modification of the FIM routine that explicitly cares for the spillover issues and gives rise to slightly different and more convenient suggestions for the BWB sensor positions.

Keywords: Optimal sensor placement, Modal sensor, EFI

1. INTRODUCTION

Optimal sensor placement (OSP) in mechanical systems and structures has become a popular and frequently discussed research topic during last ten years. Applications cover modeling, identification, fault detection, and active control of such systems as bridges (10) (9), rail wagons (15), large space structures (16). The goal is to tell the designers of the whole mechanical system where displacement, force, inertial acceleration, or other sensors are to be installed so that they are as informative as possible.

Various approaches have been developed. We will mention two in brief. The former, information based approach, is based on the analysis of the output shape matrix. An iterative elimination algorithm, denoted as EFI (for “Effective Independence”) has been developed that repeatedly deletes the lines of the initial, full output shape matrix with lowest amount of information, measured by either the trace or determinant of an underlying Fischer information matrix. See (4) for more detailed treatments and (10) (9) (16) for some case studies.

An alternative approach is based on the idea of maximizing the energy of the underlying modes in the optimally placed sensors. Related procedures lead to optimization problems over output Gramians of the system. References: (17).

Both these approaches are applied on pre-selected modes of interest. For instance, in an active damping application for a transport vehicle, see a recent report (15), the bandwidth and thus implied modes are defined according to some comfort standards and considerations regarding impact of particular modes on the loads induced in the structure. Typically, a few lower modes are selected as a result of such analysis. Resulting optimal sensors selection is subsequently called, with only those pre-selected modes in mind.

However, also those not-considered, typically mid- or high-frequency modes are still present in the process and, if excited by disturbances or the control action, they can influence the active damping system behavior in an unexpected manner. This phenomenon, denoted as spillover, cannot be captured directly by the two existing approaches mentioned above. Although some procedures have been developed that address these issues, see e.g. (18), they are based on advanced signal processing (filtering) of the measured signals and do not suggest how to modify the sensors positions themselves accordingly.

And it is exactly the problem that this paper is focused on. The aforementioned information approach is taken as the starting point. The underlying criterion is modified so that the influence of desirable modes is maximized, and those unwanted modes are minimized in the observations at the same time, see section 2. The result is a compromise where suitably chosen simple weights serve as a tuning knob for the designer. A related numerical procedure is then developed, based on the EFI approach, in section 3. Two examples are presented in section 4 where one can compare results of both approaches presented in this paper. Conclusions and suggestions for further research then follow in section 5.

2. THE EFFECTIVE INDEPENDENCE METHOD (EFI)

Optimal sensors placement techniques are extensively discussed in papers (4) (5) (6) (2) (3) (7) (10) (9). A short
overview of the EFI method follows in this section 2, adopted from (10) (9).

The aim of the EFI method is to select measurement positions that make the mode shapes readings of interest as linearly independent as possible. The method originates from the estimation theory and is based on maximization of related Fisher information matrix, measured by its determinant or trace. That is in fact equivalent to minimization of the condition number of the information matrix related to selected sensors. The number of sensors is iteratively reduced from an initially large candidate set by removing those sensors which contribute least of all the candidate position to the linear independence of the target modes readings. In the end, the remaining sensors are delivered as the optimal sensor set. As a useful guideline to stop the iterative removing process, the determinant of the Fisher information matrix can be plotted with respect to the number of sensors; if a considerable drop is identified, further reduction should be considered with care.

2.1 Structural model

The sensor placement problem can be investigated from uncoupled modal coordinates of governing structural equations as follows:

\[
\ddot{q}_i + M_i^{-1} \cdot C_i \cdot \dot{q}_i + M_i^{-1} \cdot K_i \cdot q_i = M_i^{-1} \cdot \Phi_T \cdot B_0 \cdot u + \epsilon \quad (1)
\]

\[
y = \Phi \cdot q + \epsilon = \sum_{i=1}^{N} q_i \cdot \Phi_i + \epsilon \quad (2)
\]

where \( q_i \) is the \( i \)-th modal coordinate and is also the \( i \)-th element of the vector, \( q \), in the 2\textsuperscript{nd} equation, \( M_i \), \( K_i \), and \( C_i \) are the corresponding \( i \)-th modal mass, stiffness and damping matrix, respectively, \( \Phi \) is the target mode shape (TMS) matrix with its \( i \)-th column as the \( i \)-th mass-normalized mode shape, \( B_0 \) is simply a location matrix formed by ones (corresponding to actuators) and zeros (no load), specifying the positions of the force vector \( u \). \( y \) is a measurement column vector indicating which positions of the structure are measured, and \( \epsilon \) is a stationary Gaussian white noise with zero mean and a variance of \( \sigma^2 \).

2.2 Method principle

From the output measurement, the EFI algorithm analyzes the covariance matrix of the estimate error for an efficient unbiased estimate of the modal coordinates as follows (5) (6) (2) (3) (7) (10):

\[
E \left[ \left( \dot{q} - \dot{\hat{q}} \right) \cdot \left( \dot{q} - \dot{\hat{q}} \right)^T \right] = \left[ \frac{\partial \sigma^2}{\partial q} \right]^T \cdot Q^{-1} \cdot \left[ \frac{\partial \sigma^2}{\partial q} \right] \quad (3)
\]

where \( Q \) is the Fisher information matrix, \( \sigma^2 \) represents the variance of the stationary Gaussian measurement white noise \( \epsilon \) in (2), \( E \) denote the mean value, and \( \hat{q} \) is the efficient unbiased estimate of \( q \). Maximizing \( Q \) over all sensors positions will result in the best state estimate of \( q \). \( \Psi \) denote the eigenvectors matrix according to Eigenvalues on diagonal of \( \lambda \) matrix. The EFI coefficients of the candidate sensors are computed by the following formation:

\[
E_D = [\Phi \cdot \Psi] \otimes [\Phi \cdot \Psi] \cdot \lambda^{-1} \cdot 1 \quad (4)
\]

where \( \otimes \) represents a term-by-term matrix multiplication, \( 1 \) is an \( n \times 1 \) column vector with all elements of \( 1 \). \( E_D \)'s entries are the EFI indices, which evaluate the contribution of candidate sensor locations to the linear independence of the modal partitions. Simple selection procedure is then employed to sort the elements of the \( E_D \) vector, and to remove the smallest entry at a time. The \( E_D \) coefficients are then updated according to the new modal shape matrix, and the process is repeated iteratively until the number of remaining sensors equals a preset value. The remaining DOFs serve as the measurement locations.

3. THE EFFECTIVE INDEPENDENCE METHOD WITH MODIFIED CRITERION (MEFI)

This modification was first introduced at European Control Conference held in Hungary in 2009 see (8). We will recall main idea of the method in this section. We will consider two requirements in the optimal sensor placement procedure, on top of the classical EFI approach, the sensors configuration should also minimize spillover (11) (12) (13) (14) of unwanted higher modes. We use the information approach to OSP based on the EFI method and modify the underlying criterion to meet both of our requirements (maximize useful signals and minimize spillover of unwanted modes).

3.1 Method principle

The modified criterion is based on the EFI reasoning presented above. Main task of the pure EFI is just to maximize information on desired modes through optimal configuration of sensors (measurements) expressed by the Fisher information matrix (FIM), or its trace or determinant respectively. The modified criterion we propose reads:

\[
J_{MEFI} = \alpha J_{EFI} + (1-\alpha) J_{SNR} \quad (5)
\]

stands for the standard EFI part (maximize the information content for those desirable modes), and

\[
J_{SNR} = \max_{[i,j,k] \in \Omega} \left[ \frac{\text{trace} \left( Q^m_{[i,j,k]} \right)}{\text{trace} \left( Q^n_{[i,j,k]} \right)} \right] \quad (7)
\]

is a newly added term to penalize the unwanted mode shapes in sensors readings. \( \Omega \) is the set of all candidate triples of sensors (we are considering three sensors to selected to simplify indexing). \( Q^m_{[i,j,k]} \) is the Fisher information matrix (see (3)) for \( m \)\textsuperscript{th} modes (those to be captured), whereas \( Q^n_{[i,j,k]} \) is the Fisher information matrix for the unwanted modes. The coefficient \( \alpha \in (0,1) \) serves as a tuning parameter and defines the relative importance of each part of the criterion.
Now we have an accordingly modified criterion. Next task is to modify the EFI heuristic in a very similar manner. Critical part of EFI method is in evaluation of $E_D$ vector (see (4)), modified evaluation takes the following shape:

$$
E_{DM} = \alpha E_D + (1 - \alpha) E_{DSNR}
$$

$$
E_D = \frac{[\Phi \cdot \Psi] \otimes [\Phi \cdot \Psi] \cdot \lambda^{-1} \cdot 1}{[\Phi^m \cdot \Psi^m] \otimes [\Phi^m \cdot \Psi^m] \cdot \lambda^m - 1}
$$

$$
E_{DSNR} = \frac{[\Phi^n \cdot \Psi^n] \otimes [\Phi^n \cdot \Psi^n] \cdot \lambda^n - 1}{[\Phi^m \cdot \Psi^m] \otimes [\Phi^m \cdot \Psi^m] \cdot \lambda^m - 1}
$$

Note that potential numerical issues near the nodes points are covered by the mapping function (8) applied on $E_D$ and $E_{DSNR}$ vector.

4. BWB RESULTS

ACFA 2020 is a collaborative research project funded by the European Commission under the seventh research framework programme (FP7). The project deals with innovative active control concepts for ultra efficient 2020 aircraft configurations like the blended wing body (BWB) aircraft (see Fig. 1 and 2). The Advisory Council for Aeronautics Research in Europe (ACARE) formulated the "ACARE vision 2020", which aims for 50% reduced fuel consumption and related CO2 emissions per passenger-kilometre and reduction of external noise. To meet these goals is very important to minimize the environmental impact of air traffic but also of vital interest for the aircraft industry to enable future growth. Blended Wing Body type aircraft configurations are seen as the most promising future concept to fulfill the ACARE vision 2020 goals because aircraft efficiency can be dramatically increased through minimization of the wetted area and reducing of structural load and vibration by active damping in a integrated control law design (adopted from (1)).

![Fig. 1. BWB FEM structure.](image1.png)

The most significant modes of the aircraft are first symmetrical and anti-symmetrical wing bending modes (in frequency $1^{st}$ and $2^{nd}$ modes). Shape of the first and second aircraft mode modeled in ANSYS can be seen from Fig. 4 and 5. The target mode shapes of these modes are plotted in Fig. 3. For all next considerations we will assume these modes to be controlled and than we need to maximize information content of these modes in measurement.

The second symmetrical and anti-symmetrical modes, also called engine modes (in frequency $3^{rd}$ and $4^{th}$ modes) are considered as a non-controlled modes and we need to minimize information content of these modes in measurement. Shape of the third and fourth aircraft modes modeled in ANSYS can be seen from Fig. 7 and 8 and the target mode shapes are plotted in Fig. 6.

![Fig. 2. BWB visualization.](image2.png)

![Fig. 3. Shape of $1^{st}$ and $2^{nd}$ modes.](image3.png)

![Fig. 4. Shape of $1^{st}$ mode.](image4.png)
Fig. 5. Shape of 2nd mode.

Fig. 6. Shape of 3rd and 4th modes.

Fig. 7. Shape of 3rd mode.

4.1 Results - EFI

The EFI algorithm was first used to select optimal sensors from original set of all available measurements. Unfortunately we are not able to focus on desired or unwanted modes in this case, because goal of EFI approach is to maximize reading of all participated modes. Only possibility is to maximize captured information content of desired modes (in our case 1st and 2nd mode). Result of optimization is show in Fig. 9 where one can see resulting set of sensor. Same set is plotted in mode shape of desired modes (in our case 1st and 2nd mode) Fig. 10 and in shape of not-required modes (in our case 3rd and 4th mode) Fig. 11.

Fig. 8. Shape of 4th mode.

Fig. 9. Optimal sensors position.

Fig. 10. Optimal sensors position plotted in required modes shapes.

One can see that the maximization of information content of desired modes yields to really hight capture of information content of not-required modes.
4.2 Results - MEFI

The ability to distinguish between particular modes in measurement simply by optimization of appropriate sensor configuration is critical in this application due to presence of more flexible modes in a narrow frequency range of 0-10 Hz. We cannot therefore rely on signal processing (filtering), and we have to think of a smart sensors configuration instead. Results of optimization for case of first and second modes as required versus third and fourth modes to be rejected are plotted in Fig. 12. One can see that information content of required modes captured by this configuration of sensors is thousand times higher than information content of not-required modes (SNR approach 56dB). Selected sensors are superimposed into target mode shapes. One can see from Fig. 13 that higher deflections of wings during first symmetrical and anti-symmetrical bending modes are at more outboard positions. On the other hand, the nodes (zero deflection of wings due to particular mode) of the second symmetrical and anti-symmetrical wing bending modes are situated in the second third of wings lengths as can be seen from Fig. 14. Sensors location optimization therefore results in positions near the most outboard nodes of the not-required modes.

Fig. 11. Optimal sensors position plotted in not-required modes shapes.

Fig. 12. Optimal sensors position. Shapes. One can see from Fig. 13 that higher deflections of wings during first symmetrical and anti-symmetrical bending modes are at more outboard positions. On the other hand, the nodes (zero deflection of wings due to particular mode) of the second symmetrical and anti-symmetrical wing bending modes are situated in the second third of wings lengths as can be seen from Fig. 14. Sensors location optimization therefore results in positions near the most outboard nodes of the not-required modes.

Fig. 13. Optimal sensors position plotted in required modes shapes.

Fig. 14. Optimal sensors position plotted in not-required modes shapes.

Results for the EFI method show maximization of reading of considered modes (see Fig. 10), as required, however, the influence of disturbing high-order modes (and hence the risk of spillover) remains rather high. The reason is that the standard EFI procedure does not feature any technical means how to express such a requirement explicitly. Note that a-posteriori treatment of those unwanted modes (e.g. by filtering the sensors signals) can be really hard or even impossible as the frequency-spacing of particular structural modes can be (and is, typically) very dense. On the contrary, using our modification to the criterion, the sensors locations are modified slightly, capturing still enough information on the modes of interest, and reducing strongly readings of unwanted modes in the measurements themselves.
5. CONCLUSIONS

Results of EFI method and its modification applied on the BWB type aircraft were presented in this paper. Aim of pure EFI heuristic is to maximize readings of considered modes by selection of a suitable subset of sensors from the initial large set. Disadvantage of this method is that there is no explicit way how to attenuate readings of unwanted higher modes. Modification of the standard EFI criterion was therefore applied to accommodate this requirement. Main contribution of this paper was to execute and assess these two approaches in the case study of a prospective BWB large passenger aircraft, and present and discuss related findings.

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