Investigation of active damping strategies applied on the aircraft engine with comparison to the passively damped system

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Abstract

To improve the comfort in the fuselage by reducing the vibration from the engine, the active damping method has been studied and compared with the passively damped system with squeeze film dampers. In the active control method, the positions of actuators play an important role in the effectiveness of vibration reduction. This study is focused on the capability of three actuator placement approaches along the vibration transmission path to deal with the vibration induced by an unbalanced rotor in the engine. They have been investigated in two aspects: optimal effectiveness over the operating frequency range of the rotor and reduction effectiveness at a certain frequency with FxLMS algorithm in the time domain. The optimization results show that, in terms of root mean square acceleration at the joints between the fuselage and the mount system, the actuation at the vibration source (approach 1) has an average of 30.5 dB reduction, while the actuation on the suspension inside the engine (approach 2) and the actuation on the mount system outside the engine (approach 3) yield relatively uniform improvement with the averages of 15.9 dB and 10.1 dB, respectively. The realizable effectiveness with FxLMS algorithm in the time domain is evaluated in acceleration and mechanical power. In terms of root mean square acceleration, the vibration is reduced by 9.0 dB, 12.9 dB and 13.0 dB with approaches 1, 2 & 3, respectively, at the Max. Take-off state. Compared with the optimization results at this frequency, it shows the capability of FxLMS as a control algorithm to realize the potential reduction effectiveness with each actuation approach in such a complex system. The results in terms of power give an inside view of the vibration reduction with each approach, indicating the importance and advantages of this criterion.

Nomenclature

d_s  Damping of SFDs
k_s  Stiffness of SFDs
k_r  Stiffness of rigid connections
k_a  Stiffness of actuators

Abbreviation

ActBRG  Active bearing
ActMNT  Active engine mount
ActInSus  Active internal suspension
ASC  Active structural control
AVA  Active vibration absorber
FxLMS  Filtered x least mean square algorithm
HPR  High pressure rotor
JntENG  The joints between the engine and the mount system
**Introduction**

The engine-induced vibration, caused mostly by the unbalance on the rotor, reduces the comfort level in the fuselage of a business jet. This undesired vibration can be attenuated using either passive or active damping techniques.

Passive methods in the past years can be categorized into two groups; one is to use the squeeze film damper (SFD) on the bearing to reduce the vibration at the source of the unbalance and the other is to use the passive engine mount to isolate the fuselage from the vibration of the engine. SFDs are widely used for the vibration reduction of the aircraft engine [1]. In the passive engine mount application, different devices can be used, such as solid blocks of rubber, fluid mount, vibration absorbers, etc. [2] [3] [4] [5].

These passive damping strategies yield good effectiveness at certain frequencies. However, they usually need techniques which increase the weight, such as the addition of isolating spring and dampers, or require complex construction inside the engine, e.g. the oil supply system for the SFDs at the bearing of the rotor, or bring difficulty in the design process, e.g. dealing with the nonlinearity in the SFD application [6]. Moreover, these passive techniques do not always provide sufficient bandwidth or attenuation to damp the vibration. Recently active methods have drawn much attention to overcome the disadvantages of the passive methods.

Various active methods are mainly focused on actuating the engine mount, to build up an active isolation system. In such systems, higher forces can be achieved and enhanced isolation over a broader range can be provided [7]. It has been applied on products, which are already in market [8]. In the realm of active vibration control, another approach is the active structural control (ASC), in which the active vibration absorber (AVA) or the actuator vibrates a structural component at a frequency to cancel the input disturbance. The AVAs or actuators are often preferably attached to the mount system, such as to the yoke [9], or to the fuselage, such as to the interior surface of an aircraft's fuselage wall [10]. And in some of the ASC application with actuators, the positioning of the actuators is slightly more demanding than the AVA, e.g. it is stated in [11] that in an ASC application for the helicopter the actuators positioned in the housing extra built along the side of the cabin exterior bring optimal effectiveness in vibration reduction. Generally speaking, ASC control systems provide larger dynamic forces and operating range is wider than the passive control. They are normally easy to be integrated or retrofitted and the safety issue is not critical.

In the past studies on active damping application, the positions of the active system are limited on the fuselage and the mount system, i.e. outside the engine and on the very downstream of the vibration transmission path. In these cases, on one side, the negative effect caused by the vibration on the upstream cannot be targeted controlled; on the other, when the vibration is already spread on a structure with complex dynamic behavior, such as on the fuselage, the field of vibration will be complex and hard to deal with.
Based on study on the vibration reduction methods and the approaches of actuator placement in the past years, two approaches of actuator placement inside the engine for active damping were proposed and compared with two benchmarks: the passive system damped with SFDs and the active system in the market - the engine with active mounts.

First of all, the actuator positions of each approach will be introduced. Then the optimal reduction effectiveness, which the active damping with different approaches can yield, will be predicted through the optimization results in the frequency domain, according to the method in [12]. Lastly, FxLMS is used to realize the active control in the time domain, and in this part the results in terms of two evaluation criteria of vibration, i.e. acceleration and power, will be compared, which also leads to the inference about the mechanism of the active damping with each approach.

**Approaches of Actuator Placement**

The active methods with different actuation positions were studied on a reference model of a left engine provided by a partner company. It consists of a two-spool engine with a high pressure rotor (HPR) and a low pressure rotor (LPR) [13], a section of the fuselage and the engine mount system (MNT), which connects the first two parts. It allows taking consideration of the dynamic characteristics of the whole aircraft system. Based on this reference model, according to different bearing configurations with actuators and SFDs and considering the necessity to integrate control strategies, four state space models have been generated to study the following approaches (see [14] for the details of the models).

The vibration transmission path is shown with the dotted arrows in Fig. 1. The actuator placement approaches are also numbered illustrated with solid arrows and the red circles point the sensor positions of each approach.

**Approach 1 - Active bearing (ActBRG):** The front supporting bearing of the unbalanced rotor is actuated by two orthogonally placed actuators and the rear bearing is not actuated, considering the negative condition of high temperature at the rear bearing. The sensors are assumed to be at the bearings both in the front and in the rear, measuring the acceleration which is transmitted from the unbalanced rotor to the engine.

**Approach 2 - Active internal suspension (ActInSus):** This approach uses the internal suspension inside the engine. Actuators are placed in the hollow struts in the front and attached to the links in the rear. Both these struts and links are a section of the transmission path of the vibration originating from the unbalanced rotor. One end of the struts in the front connects the bearing shell and the other end shares the same position as the joints between the engine and the MNT (JntENG). One end of the links in the rear also shares the same
position as JntENG and the other end is attached to the core engine. The sensors are assumed to be at the JntENG, measuring the vibration in acceleration, which is transmitted from the engine to the MNT.

Approach 3 - Active engine mount (ActMNT): All links of the MNT, except those which transmit the thrust, are actuated. This concept has been patented [7] and its application is available on the market [8]. The other structure of the MNT, e.g. the yoke, is not considered as actuated in this study, but it transmits vibration. The sensors are assumed to be at the joints between the fuselage and the MNT (JntFL), measuring the vibration in acceleration, which is transmitted from the MNT to the fuselage.

Each approach was applied on its own corresponding model [14]. The passive system only with SFDs was set as the benchmark to these three active systems.

Optimization in the Frequency Domain

The LPR can be balanced after the assembly, while the unbalance of the HPR cannot be dealt with, because it is not accessible after the assembly [15]. So the unbalance of the HPR is set as the cause of vibration. It is assumed to be on the middle of the rotor for the first bending mode of the HPR.

To find out the ideally optimal effectiveness with the three actuator placement approaches, the optimization procedure was carried out for each single frequency, based on the frequency response of the corresponding system under the afore-mentioned unbalance. The control actuation was modelled as a pair of axial forces acting at the mount ends or between the bearing and the surrounding structure of the bearing. The target is to minimize the root mean square acceleration at JntFL for optimal comfort level at the fuselage, according to the method introduced in [12].

Fig. 2 shows the results of the optimally controlled system with SFDs. The reduction is calculated with respect to the passive system with SFDs and presented in dB (mm/s²). As shown in the robustness study [14], the interesting frequency range can be narrowed down to frequencies over 0.4 (normalized value), where the resonances are much higher. The reduction level with ActMNT (green) fluctuates around the average of 10.1 dB reduction, while ActBRG, with an average of 30.5 dB, yields much more reduction at most frequencies than the other two approaches. The system with the ActInSus approach shows a better performance with an average of 15.9 dB than ActMNT, except at the frequency around 9.6. Comparing ActInSus and ActBRG, they yield almost the same effectiveness between 0.6 and 0.9 and ActBRG is much better than ActInSus at the other frequencies.

Figure 2. Vibration reduction in optimally controlled systems with SFDs

ActBRG reduces the vibration at JntFL, in the way of damping the vibration at the beginning of the transmission path before it is spread over the structure of the engine. Referring to Fig. 1, although ActMNT effects on JntFL directly, it does not have such good effectiveness as ActBRG, because the vibration has already
been distributed at the stage of MNT and will be transmitted not only through the controlled links but also the other uncontrolled structure of the MNT, e.g. the yoke. The better performance of the ActInSus approach than ActMNT can be explained with the transmission path: As shown in Fig. 1, it works on the earlier stage of the path than ActMNT and controls all the links which transmit the vibration at its own stage. From its worse performance at around the frequency of 9.6, it can be inferred that only the fuselage is involved in the eigenmode at this frequency and the actuation at the engine side as ActInSus does has less influence on it.

**FxLMS Implementation in the Time Domain**

In the section above, the optimal reduction effectiveness with each approach gives an overview about the potential of the actuation positions in vibration reduction. In this section, the control algorithm is implemented and shows how much the potential can be realized.

In the current application of the active engine mount approach, Filtered-x Least Mean Square (FxLMS) algorithm and Filtered-u Least Mean Square have been successfully implemented for the active damping on the fuselage [8] [9]. In this study, FxLMS has been applied for each approach (refer to [14] for detail). To reduce the vibration caused by the unbalance, the unbalance forces are set as the reference signal. The errors in acceleration are measured at the sensor positions as described in Section ‘Approaches of actuator placement’.

The control design was carried out for the actuation approaches combined with SFDs, when the rotors rotate at constant speeds. Here the rotation speeds at the Max. Take-off state are taken as an example.

**Criterion: acceleration**

First of all, the acceleration of JntFL, as one of the important criteria of comfort, is evaluated. Fig. 3 shows the acceleration at a front link and a rear link of JntFL in the open-loop system and the close-loop systems with the application of FxLMS. All three approaches are more effective on the rear link than on the front link at this frequency. ActBRG performs the best with respect to the vibration reduction in the front, while it is ranked the last with respect to the rear reduction. It is presumably due to the relative lack of actuation in the rear in the ActBRG approach, due to the high environment temperature. ActMNT and ActInSus almost overlap each other in terms of the rear acceleration, because the actuation of these two approaches covers all the transmission links in the rear at their own transmission stage. In the front, ActBRG, reducing the vibration at the source, yields the best result, and ActInSus performs slightly worse than ActMNT, which could result from the worse observability at this frequency with the sensors only placed at JntENG.

**Figure 3. Reduction in acceleration at one of the front and one of the rear joints of JntFL with FxLMS**

For the overall evaluation, the reduction in rms acceleration of all the links in the front and all the links in the rear of JntFL is
listed in Table 1 with three approaches. ActBRG, reducing the vibration at the source, controls the vibration in the front and in the rear at the same level. ActInSus and ActMNT show similar effectiveness: roughly half of the reduction with ActBRG in the front and twice of it in the rear. Different from ActBRG, these two approaches perform much better in the rear than in the front, indicating the more effective rear actuation at this frequency.

Table 2 records the vibration reduction in the same criterion from the optimization results. Comparing Table 1 and Table 2, it is found that FxLMS can realize in the front 87.5% and in the rear 78.1% of the optimal effectiveness in the case of ActBRG and the full potential effectiveness in the case of ActMNT and almost the full in the rear of the case of ActInSus. With ActInSus, there is a relative big deviation between the realized effectiveness with FxLMS and the optimal in the front.

Table 1. Realizable reduction with FxLMS in rms acceleration in the front links and the rear links of JntFL, at the frequency of Max. Take-off state

<table>
<thead>
<tr>
<th>In dB</th>
<th>Front</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>ActBRG</td>
<td>-6.3</td>
<td>-6.4</td>
</tr>
<tr>
<td>ActInSus</td>
<td>-2.9</td>
<td>-12.6</td>
</tr>
<tr>
<td>ActMNT</td>
<td>-1.8</td>
<td>-12.9</td>
</tr>
</tbody>
</table>

Table 2. Optimal reduction in rms acceleration in the front links and the rear links of JntFL, at the frequency of Max. Take-off state

<table>
<thead>
<tr>
<th>In dB</th>
<th>Front</th>
<th>Rear</th>
</tr>
</thead>
<tbody>
<tr>
<td>ActBRG</td>
<td>-7.2</td>
<td>-8.2</td>
</tr>
<tr>
<td>ActInSus</td>
<td>-7.9</td>
<td>-13.5</td>
</tr>
<tr>
<td>ActMNT</td>
<td>-1.6</td>
<td>-11.7</td>
</tr>
</tbody>
</table>

Criterion: power

Besides acceleration, power should be also investigated for the following two reasons: (1) The acceleration is an important evaluation criterion of the sensed comfort in the vehicle [17]. However, before reaching to the comfort-sensing position, where the people are located, the vibration is transmitted in the form of energy and the analysis of acceleration on the transmission path is insufficient to come to any conclusion. In this study, the sensors are placed to measure the acceleration at JntFL, directly at the fuselage. Nevertheless, strictly speaking, JntFL are not the end of the vibration transmission path, for the vibration will be further spread over the fuselage in the form of vibrational energy to the sitting positions. (2) This single parameter can be used to describe the dynamics of the system in a consistent manner [16]. The acceleration is evaluated in different degrees of freedom at each joint, however, in power, the vibration in different degrees of freedom can be added up as one, indicating the transmitted vibration at a joint or several joints.

Therefore, the power of transmitted vibration is additionally proposed to evaluate the effectiveness of vibration reduction. The power is the product of the force or the moment due to the elongation or bending of the link and the linear or angular velocity at the joint. Positive power means that the vibration is transmitted into the fuselage and vice versa.

Taking the two links, whose acceleration is shown in Fig. 3, for example, Fig. 4 and Fig. 5 show the power transmitted between the engine and the fuselage through these links when the responses reach steady state with different damping strategies. The black lines represent the power transmission in the passively damped system, in which the power is transmitted into the fuselage for most of the time and absorbed by the engine for a small portion of time both in the
front and in the rear at this frequency. The green line in Fig. 4 shows that the power transmitted into the fuselage is increased in the front, and it shows in Fig. 5 that the power is absorbed through the rear link in the application of ActMNT. The power input through the front link with ActInSus is also slightly increased, while that with ActBRG is largely decreased. The blue and red lines in Fig. 5 indicate that the approaches of ActBRG and ActMNT reduce the power between the fuselage and the engine in both directions.

![Figure 4. Power into the fuselage through one of the front links of the MNT](image)

The plots in Fig. 3 and Fig. 4 & 5 show the vibration at the same positions, i.e. at one of the front and one of the rear joints of JntFL, in terms of linear acceleration in the direction of the links and power through forces and moments of all degrees of freedom, respectively. Generally, the reduction in acceleration does not necessarily indicate a decrease in power, especially proved by the front link, comparing the left plot of Fig. 3 and Fig. 4. It can be inferred that the decrease of acceleration in the front with ActMNT is contributed by the absorption of power in the rear, because the transmitted power in the front is actually increased and the power in the rear is shifted to the negative value. Similarly, the reduction of acceleration in the front with ActInSus is presumably due to the reduction of power in the rear. Therefore, the rear actuation in the application of ActMNT and ActInSus is more effective than the front actuation at this frequency. The indication of acceleration and that of power are roughly consistent in the application of ActBRG: In both criteria, it is the best according to the results of the front link and the worst according to those of the rear link among the three approaches.

**Summary**

This study started with the system consisting of engine, mount system and section of the fuselage, which is a good representation of the aircraft system for the investigation of reduction of vibration induced by the unbalance. Based on the models built with different bearing configurations, the optimal effectiveness in the frequency domain and the realizable effectiveness with FxLMS in the time domain have been investigated.

With the rms acceleration at JntFL as optimization target, ActBRG, ActInSus and ActMNT can yield an average reduction of 30.5 dB, 15.9 dB and 10.1 dB in terms of the rms acceleration at JntFL, respectively. The control at an earlier stage of the vibration transmission path yields an advantage of higher reduction in such an engine-fuselage system. It can be concluded that when the vibration is spread over at a
stage, it needs more control effort either in number of actuation positions or in magnitude, referring to the case of ActMNT.

FxLMS was used to realize the active damping with each approach and sensors collocated with actuators. The results were generated and discussed in two criteria.

The results in acceleration not only indicate the vibration reduction levels, but also show to which extent FxLMS can make use of the potential of each actuation approach, compared with the optimization results at the same frequency. As for the former aspect, it shows that ActBRG, reducing the vibration at the source, yields good effectiveness both in the front and in the rear, while the other two approaches perform unevenly with respect to the front and the rear, due to the energy distribution at a later stage in a relative complex structure. As for the latter aspect, it can be stated that a high percentage of the optimal effectiveness can be realized with FxLMS.

Power, supplementing the evaluation in acceleration, has several advantages. The results in power give insight of the power flow with each actuation approach. In this case study, it shows that ActBRG can reduce both the positive and negative power in the front and in the rear, due to its advantage to reduce the vibration at the source. To reduce the overall vibration both in the front and in the rear, the other two approaches work in such a way at the Max. Take-off frequency: The front link of the active system with ActMNT transmits more power into the fuselage and the rear link makes the engine absorb more power, while ActInSus is capable to reduce the power input in the rear and has little effect on the front link.

This study gives an overview of the effectiveness of three approaches of actuator placement, located on different positions of the vibration transmission path. It can be inferred not only from the results but also from the mechanism of vibration transmission that the two approaches inside the engine, i.e. ActBRG and ActInSus, have great potential to provide better reduction effectiveness than ActMNT and should be further studied for other frequencies and also the feasibility should be investigated. It also inspires to discover other positions inside the engine, which have the advantages of good reduction effectiveness, less effort and good feasibility. FxLMS is an effective control algorithm to realize control effectiveness in such a complex system, and its stability and convergence speed should be improved for different frequencies. Since power is an important criterion, it should be investigated if the reduction can be improved, when power is fed back into the controller, instead of acceleration alone.

References


