

Performance-Limit Oriented Active Control of Vibration: Past, Present & Future Perspectives

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Abstract: Conventional active vibration control methodologies predominantly focus on achieving performance improvement relative to open-loop systems, rather than exploring the inherent performance boundaries imposed by physical constraints, system structures, and actuation/sensing limitations. To overcome these drawbacks, performance-limit oriented active control of vibration has emerged as a systematic design framework that aims at revealing and approaching the theoretical performance boundaries. This paper presents an overview of performance-limit oriented active vibration control from past developments, current advances, and future perspectives. Specifically, a major development in the field has been established with a “visualization technique” where performance limits can be readily determined solely based on visual inspection, yet resolving fundamental issues as existence, optimality, and performance limits of controllers, as well as evaluating the influence of constraints on optimal solutions. New developments are suggested for extensions to high-order heterogeneous complex networks, and particularly to adaptive and intelligent solutions, which enable online performance limit tracking, data-driven boundary estimation, and thus enhance robustness against uncertainties and nonlinearities. Future directions are prospected toward nonlinear performance-limit analysis and real-time computational methods under extreme conditions, and wider applications in high-end manufacturing, aerospace, and military equipment. This paper is expected to promote the in-depth development and engineering popularization of performance-limit oriented control theory and technology.

Keywords: active vibration control; performance limit; energy transfer

1. Introduction

With increasing performance requirements for modern technological systems, the associated vibration problems can become pivotal to structural integrity as well as system reliability. Conventionally, the problematic vibration can be alleviated through passive devices such as dampers. However, the passive devices are constrained by effective frequencies, weight, and size restrictions. It is thus necessitated to consider active control solutions to structural vibration attenuation and reduction.

Over the past three decades, many active control methodologies have been well-established, for example [1–6] & references therein. The approaches can be categorized into both feedforward and feedback compensations, with the latter being particularly actively pursued such as H_2/H_∞ controls, linear parametric varying control, and adaptive control, etc. It is worth noting that most of the approaches, including those feedforward ones, essentially utilize optimization-based methodology, where a certain functional norm (or performance index) is optimized



against controller parameters [7–10]. These optimization-based methods are powerful; however, they are also of trial-and-error nature. Important intuition upon the best achievable performance is not revealed, nevertheless in determining performance limits. To be specific, the conventional optimization-based approaches are difficult in handling the following issues:

- (1) Performance limit at harmonic frequency or over a finite frequency band;
- (2) Compromise among multiple performance indices;
- (3) Evaluation of control performance from specific physical parameters.

Indeed, active vibration control problem often occur at discrete harmonic frequencies or over a frequency band, thus it is necessitated to consider the problem of control optimization over a finite frequency band. Both KYP-lemma and weighting function methods can be utilized, but it is obvious that they involve complicated parameter optimization and/or even model reduction for controller implementation. Indeed, it is fair to claim that the problem of determining performance limits at a discrete frequency or over a finite frequency band is an unsolved issue.

Referring to performance limits, this points to one ultimate question to be answered: what is the performance limit of active vibration control? Indeed, the fundamental philosophy for control is to excavate system performance by taking advantage of every piece of information, e.g., internal structural properties, topology and interactions, external noise and disturbance power spectral distributions etc. We must abandon the conventional mindset that a controller is designed only to achieve performance improvement over the open-loop system. It is the author's conviction that designing a controller simply to outperform the open-loop performance is essentially meaningless without knowing the performance limit. Simply outperforming the open-loop system does not have an impact on practical engineering, since closed-control performance is actually measured with multiple indices including cost and reliability, etc. This points to the core idea of the performance-limit oriented active vibration control framework adopted in this paper. It aims at exploiting the performance limits, should the closed-loop control strategy be adopted. This is important particularly when considering the situation as imposed by physical constraints, system structure, and actuation/sensing limitations.

Thus, the paper aims to detail a specific, emerging school of thought to approach the performance-limit oriented active vibration control, namely a geometric design methodology. Section 2 introduces the past and present status of the methodology; Section 3 shall provide the future perspectives, before the final discussions are made.

2. Its Past & Present Status

2.1. Past Status

To fully demonstrate what we meant by “performance-limit oriented control,” the following generalized control structure, namely, the general control configuration, is considered as shown in Figure 1.

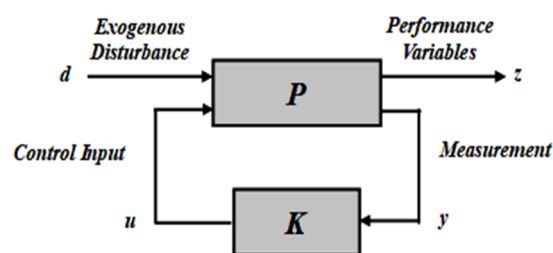


Figure 1. General control configuration.

The following design requirements are defined; namely, optimal control or design K is sought to satisfy the corresponding performance index as below:

Problem 1. $\|z\|_2/\|d\|_2 \leq \gamma$

Problem 2. $\begin{cases} \|z\|_2/\|d\|_2 \leq \gamma \\ \|y\|_2/\|d\|_2 \leq \beta \end{cases}$

Problem 3. $\begin{cases} \|z\|_2/\|d\|_2 \leq \gamma \\ \|y\|_2/\|d\|_2 \leq \beta \end{cases}$ at harmonic frequency ω_0 or over a frequency band $[\omega_1, \omega_N]$.

where γ and β are positive real numbers indicating the performance specification. It is seen clearly that Problem 1 is the conventional H_∞ design problem (VA); Problem 2 shall be defined as global vibration attenuation (GVA),

while Problem 3 can be called as global vibration attenuation over a frequency band (GVAFB). It is noted that Problem 2 GVA is different from Problem 1 VA since it requires the design to satisfy the global vibration attenuation capability. Thus, we require that “all performance variables must have improved (attenuated) performance.” However, consider the following motivating issues:

- (1) Vibration or noise problems often occur at specific harmonic frequencies or over a frequency band. It is rare to note that control can be very conservative if it is enforced over a whole frequency band, as the usual optimization-based approaches do.
- (2) Global vibration attenuation is often required, indicating that the performance variables must all be confined to avoid the issue of local optimal design resulting in global performance deterioration.

As a consequence, the GVAFB is actually more sensible and reasonable than both VA and GVA. To illustrate this claim, it is worth stressing that the issue of local optimal solutions resulting in global performance deterioration is much more common and problematic than generally recognized and can occur in a variety of applications. In marine systems, the propulsion-induced vibration at specific blade passing frequencies can propagate through the hull to other sections of the vessel, leading to significant large area hull excitation. This can cause serious structural integrity compromise associated with passenger and crew discomfort, self-noise sonar interference, and, in extreme cases, catastrophic fatigue failure. Similar problems occur in helicopter rotor systems where blade-induced aerodynamic disturbance transmits through the fuselage which not only compromises the reliability of on-board electronic equipment, but also leads to reduced flight envelopes. Also in aerospace applications, the increasing use of lightweight and flexible structures often results in wide area flow-induced disturbance that can lead to dynamic aero-elastic instabilities such as wing flutter, with the potential to cause structural failures in flight. The same issue of local optimal solution resulting in global performance deterioration also resembles itself in automotive, satellite and civil engineering applications where the local vibration is connected with the remote vibration through a transmission path. However, only one actuator is available for control action, and this presents a difficult problem to solve for the global performance requirement. It becomes increasingly necessitated with the fact that all the above scenarios are vibrating at discrete frequencies or over a frequency band. This justifies the above claim that the GVAFB is actually more sensible and reasonable than both VA and GVA in practical engineering applications.

Now, to address the GVAFB problem while demonstrating the compromise issues among the performance variables, one classical and historical method is through mixed sensitivity optimization as below:

$$\left\| \begin{array}{c} W_s(s)S(j\omega) \\ W_1(s)R_1(j\omega) \\ \vdots \\ W_n(s)R_n(j\omega) \end{array} \right\|_{\infty} \leq \gamma \quad (1)$$

Then one immediate question is: if the tradeoff problem is solved through the mixed sensitivity approach as optimized against (1), how can one obtain the best achievable performance and further analyze the tradeoffs among the performance variable? The above formulation clearly requires iterative procedures and thus of trial-and-error nature.

Indeed, most of the control-theoretic approaches treat the design problem over a full frequency band (refer to [11]). When applied to finite-frequency band or discrete harmonics for vibration control problems, the theory is such “tailored” through either weighting functions or generalized KYP-lemma. Indeed, this is a finite-frequency H_{∞} control problem, which has been discussed over the past two decades, tracing back to the Kalman–Yakubovich–Popov (KYP) lemma [12], through the heuristic approach [13], to the recent generalized Kalman–Yakubovich–Popov (GKYP) lemma based LMI approach [14]. Please see the references therein. However, it must be pointed out that the current methods are difficult in (1) handling the effect of physical parameters on system performance; and even importantly (2) obtaining performance limits. In fact, the problem of determining limit of performance is a fundamental issue that has unfortunately overlooked for many design approaches. The mixed sensitivity method takes care of this issue by minimizing H_2/H_{∞} norm for both sensitivity S and complementary sensitivity T . But the choice of weighting functions is also of rule-of-thumb nature, aiming to maintain the ideal shapes for the norms of sensitivity functions (e.g., S small in low frequencies and T small over high frequencies etc.). Important intuition on both solution existence and limit of performance particularly at any discrete frequency is thus lost. Yet these important issues are resolved within the proposed framework through intuitive geometric expressions, as demonstrated in the next subsection.

2.2. Current Progress

While having explained the motivations and contributions of the proposed method, it is assumed that the performance variables to be attenuated are defined by $X_i(j\omega) \forall i \in [1, N]$. Now it is good time to come back to the following important questions below:

- (1) Whether all performance variables $X_i(j\omega) \forall i \in [1, N]$ can be attenuated?
- (2) What is the performance limit for each performance variable?
- (3) How do the performance variables compromise with each other?

To address the above problems, a geometrically interpretable framework has been formally established by the author to quantify achievable performance regions and fundamental limits imposed by system dynamics, actuation saturation, and sensing constraints. Importantly, this paradigm has been effectively integrated with finite-frequency design—a key advancement that resolves the conflict between full-frequency optimality and practical energy efficiency. Consequently, the control design focuses upon performance limit to the frequency range of engineering interest (e.g., harmonic frequencies or over a frequency band), enabling the system to approach performance limits without amplifying high-frequency noise, a common drawback of traditional full-frequency control methods.

To illustrate the methodology, consider Figures 2 and 3 for a specific illustration—essentially, the performance index is “transformed” into the circles, e.g., α – circle indicates the performance in $X_1(j\omega)$ while β – circle indicates the performance in $X_2(j\omega)$. Leaving detailed derivations into references [15,16], the following claims stand:

- (1) A controller exists where the transmission of disturbance to both performance variables $X_1(j\omega)$ and $X_2(j\omega)$ can be attenuated simultaneously for the harmonic frequency;
- (2) Performance limit for each performance variable can be “easily” obtained as in Figure 3;
- (3) Since the two centers locates outside each other, the performances in $X_1(j\omega)$ and $X_2(j\omega)$ will have to compromise.

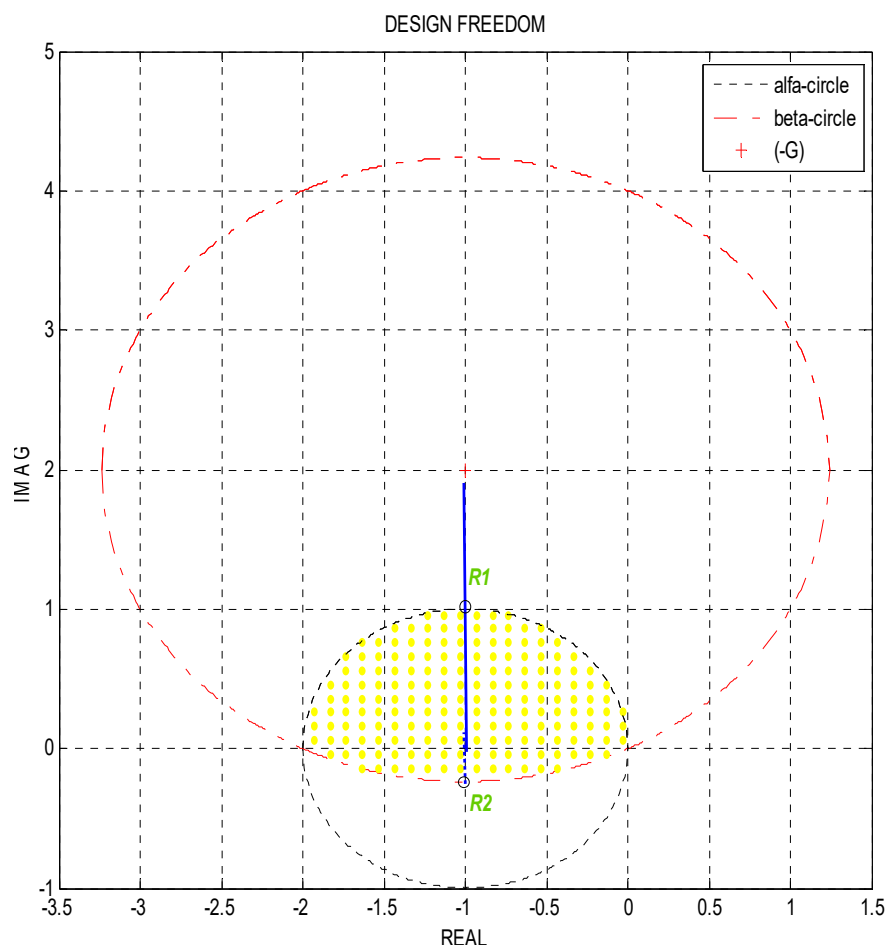


Figure 2. Geometric representation of performance, shaded area indicating simultaneous attenuation.

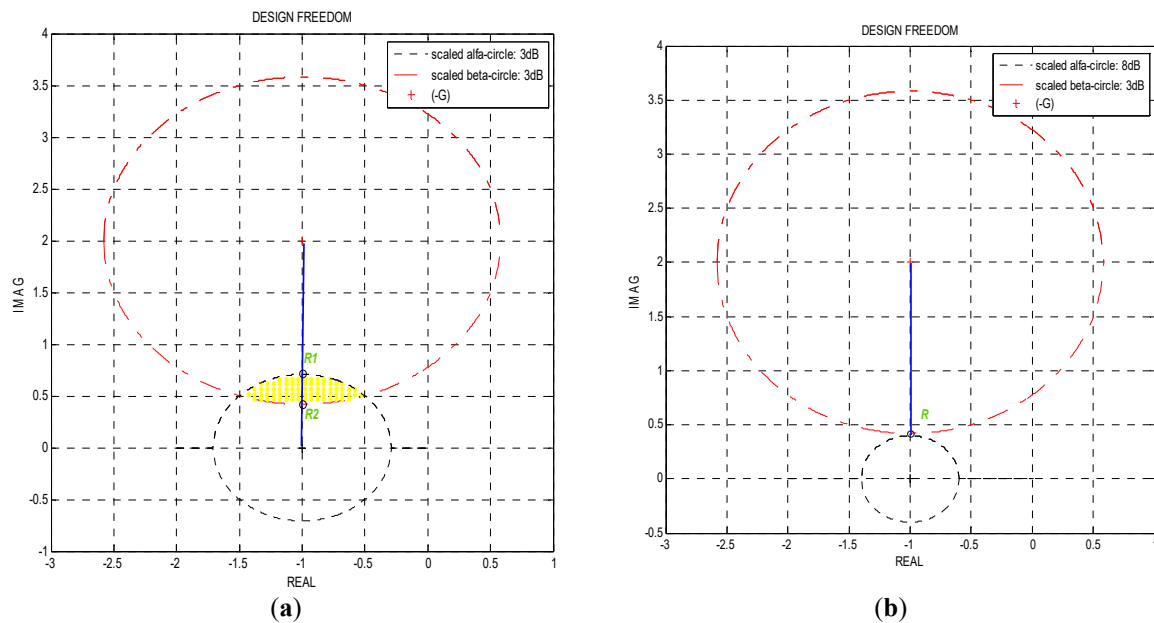


Figure 3. Performance limit for active vibration control: while (3 dB, 3 dB) simultaneous reduction in both performance variables is achievable in (a), the performance reaches its limit for an (8 dB, 3 dB) specification in (b).

It is thus seen clearly that the above important information can be obtained by the proposed methodology, while it can be difficult to resolve through the available approaches. And it is “legitimate” to claim that a performance-limit-oriented approach is established, providing a new design methodology for active vibration control, in addition to taking the optimal constrained solutions into account within the same framework.

To summarize, a systematic design methodology has been established with a “visualization technique” where performance limit can be readily determined solely based on visual inspections. Indeed, through the geometric representation of the performance specifications, the following fundamental issues can all be resolved within the geometric framework as:

- (1) existence of feasible controllers;
- (2) optimality of controllers;
- (3) performance limit of controllers;
- (4) compromizability among the performance specifications;
- (5) synthesis of controllers;
- (6) influence of constraints on optimal solutions.

Consequently, the state-of-the-art is refined with a new approach complementary to those optimization-based routines, where extra effort would have to be exercised to disclose the compromizability of performance specifications. It is claimed that the limit of performance is obtained, where other methods can be benchmarked against the best achievable performance. This forms the distinctive novelty of the methodology—the proposed framework essentially results in a new design methodology—performance-limit oriented active control of vibration. It is initiated by the author with the project “Active Control for Performance Limit” (ACPL). A series of fundamental results have been obtained and have been disseminated. Please refer to the monograph [6] for collections of the results. Particular attentions are made to the novel energy harvesting vibration absorbers [15,16] as well as to applications as listed in the patents [17,18].

The framework has also been extended into multi-frequency and broad-band controls [19]. For the broadband case, convex optimization tools such as linear matrix inequalities (LMIs) and semidefinite programming (SDP) have been adopted to solve finite-frequency constrained performance-limit problems, yielding tractable and implementable controllers.

3. Future Perspectives

3.1. Performance-Limit Oriented Active Control of Vibration with Adaptivity and Intelligence

Previous development has assumed that the system has fixed parameters with linear dynamics. However, for large operational envelope, the system dynamics must be nonlinear. Henceforth the extension to nonlinear system is necessitated. One promising strategy is the introduction of adaptive and intelligent methodologies. On one hand,

adaptive control strategies shall provide a performance-limit framework with online learning and real-time adjustment capabilities. Instead of using fixed, offline-calculated performance boundaries, adaptive schemes can dynamically update controller parameters while maintaining the system performance towards the best achievable performance—performance limits. This innovation ensures that the system can continuously approach the optimal performance boundary even in uncertain environments.

On the other hand, intelligent algorithms, as represented by neural networks and reinforcement learning, further revolutionize performance-limit oriented design. They relax the heavy dependence on accurate mathematical models, enabling the estimation and tracking of performance limits for complex, nonlinear, and unstructured systems. By combining data-driven perception and decision-making, intelligent methods extend the application scope of performance-limit control and enhance its ability to handle strong uncertainties and multi-objective constraints.

In summary, the integration of adaptive and intelligent development with performance-limit oriented active control of vibration aims to develop truly optimal, feasible, and energy-efficient vibration suppression strategies for complex engineering systems. This not only improves the adaptability, robustness, and optimality of vibration suppression, but also opens a new path toward the theoretical performance boundaries under complex engineering conditions.

3.2. Performance-Limit Oriented Active Control of Vibration for Energy Transfer and High-End Equipment Applications

One important concept of vibration distribution has been proposed by the author, where part of the performance variables is required to be attenuated while the remaining to be enhanced. This concept is a new development: it is well-known in active control field, all performance variables need to be attenuated for vibration control and all performance variables require to be enhanced for energy harvesting. This concept of combining vibration control and energy harvesting within one structure is coined as “vibration distribution” which further leads to another important concept, namely “energy transfer.” Indeed, both active control and energy harvesting would require a significant amount of energy to fulfill corresponding design objectives. One natural idea is to “re-distribute” the energy at different locations for each purpose. This vibration distribution of energy transfer can also lead to novel applications, e.g., in submarine systems, vibration must be attenuated to relieve the danger of sonar detection, however structural silence can be very difficult (if not impossible) to achieve. Recent development involves attenuating vibration at some (specific) locations while (intentionally) enhancing vibration at some other locations. The enhanced vibration can be tuned into high frequency range which is “soaked” quickly by the seawater without long-distance propagation. Performance-limit oriented active control of vibration for energy transfer thus provides a systematic paradigm to address the critical issue.

4. Discussions

Given the motivations and proposed design approaches, together with the future perspectives mentioned above, performance-limit oriented active vibration control still faces unresolved challenges, including limited real-time computational tools for large-scale systems, and an incomplete bridge between theoretical performance limits and practical controller tuning. This calls upon not only theoretical investigations, but also promotion of collaboration across both academic and industrial fields. Three suggestions can be made:

- (1) Deep theoretical investigation into advancing the fusion of performance-limit oriented control and finite-frequency design must be carried out to widen the concept of design towards performance limit;
- (2) International conferences and even an Association/Federation can be established promoting performance-limit oriented design, reminding control engineers to focus upon efforts for analyzing limit of performances;
- (3) Industrial engineers are invited to attend the conferences or be members of the Association/Federation, so that the real industrial control requirements can be brought to academics, allowing the dissemination of the control designs;

These gaps, combined with the long-standing neglect of performance-limit oriented design, highlight the necessity of further research in this area—to develop truly optimal, feasible, and energy-efficient vibration suppression strategies for complex engineering systems.

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Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data are available with request to the author.

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Conflicts of Interest

The author declares no conflict of interest.

Use of AI and AI-Assisted Technologies

During the preparation of this work, the author used DeepSeek to polish some sentences. After using this tool, the author reviewed and edited the content as needed and takes full responsibility for the content of the published article.

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