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Auto-Tuning Adaptive Supervisory Control of Single-Plane Active Balancing Systems

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abstract

Adaptive influence-coefficient methods have proven successful at controlling unbalance-induced vibration of rotating machinery without requiring *a priori* knowledge of machine dynamics. If initial influence estimates are inaccurate, however, vibration may become worse temporarily before the estimation converges. An auto-tuning method is presented here that adjusts adaptive "gain" parameters during control convergence. The auto-tuning method limits worst-case vibration while allowing the same convergence rate as conventional "fixed-parameter" adaptive control. A supervisory control method is also introduced that automatically selects vibration thresholds for enabling and disabling control based on estimated plant dynamics. Experimental results verify the effectiveness of the auto-tuning approach.

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AUTO-TUNING ADAPTIVE SUPERVISORY CONTROL OF SINGLE-PLANE ACTIVE BALANCING SYSTEMS

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ABSTRACT

Adaptive influence-coefficient methods have proven successful at controlling unbalance-induced vibration of rotating machinery without requiring *a priori* knowledge of machine dynamics. If initial influence estimates are inaccurate, however, vibration may become worse temporarily before the estimation converges. An auto-tuning method is presented here that adjusts adaptive "gain" parameters during control convergence. The auto-tuning method limits worst-case vibration while allowing the same convergence rate as conventional "fixed-parameter" adaptive control. A supervisory control method is also introduced that automatically selects vibration thresholds for enabling and disabling control based on estimated plant dynamics. Experimental results verify the effectiveness of the auto-tuning approach.

INTRODUCTION

Mass imbalance-induced vibration affects the precision and reliability of rotating machinery involved in metal cutting, petro-chemical processing, and power generation. "Influence-coefficient" based control methods have been developed for rejecting unbalance-induced steady-state vibration of rotating machines (Lee et al., 1990; Zeng and Wang, 1998). Research has been shown that such control will be stable if the influence coefficient estimate is sufficiently accurate (Knospe et al., 1997). Adaptive control with on-line system-identification can often succeed without any *a priori* knowledge of the influence coefficient, even in the worst case scenario where the influence estimate is 180° out of phase with the actual influence coefficient (Dyer and Ni, 1999). However, no strict examination of the fully integrated adaptive control stability has been undertaken. This paper presents a formal stability analysis of the adaptive influence coefficient control for certain typical conditions. The stability analysis highlights a potential deficiency in the adaptive control performance.

Though the adaptive control is shown to be stable even for inaccurate initial influence coefficient estimates, there is no guarantee that the controlled vibration will not temporarily become unacceptably large prior to estimation convergence. To address this concern, an automatic tuning method was developed that varies adaptive control and estimation gain parameters during each control iteration based on a measure of estimation convergence. This "auto-tuning" method is shown to limit the worst case vibration during control adaptation while not slowing down control response.

For active balancing on such applications as machine tools, supervisory control is often necessary for integration with the machine tool controller. Vibration thresholds or "limits" are typically selected as criteria for enabling and disabling active balancing control. To eliminate the need to apply special engineering knowledge in setting these limits for each application, an automatic on-line limit selection algorithm is also presented here. The algorithm continually considers machine dynamics, actuator resolution and measurement noise to set appropriate control limits. Experimental results provide a comparison between the auto-tuning control and conventional adaptive control.

STABILITY OF ADAPTIVE INFLUENCE COEFFICIENT CONTROL

The steady rotational speed-synchronous vibration "error" output e_k (a complex scalar) at a given discrete control iteration k can usually be assumed to be a linear function of the effect of the active balance input w_k through the influence coefficient c and the cumulated effect of all rotor-synchronous disturbances d (w_k, c and d are also complex scalars).

$$e_k = cw_k + d \tag{1}$$

The active balancing controller commands the balance weight correction w_{k+1} to minimize vibration according to the following control law (Dyer and Ni, 1999):

$$w_{k+1} = w_k - \alpha \frac{e_k}{\hat{c}_k} \tag{2}$$

where α is a real-valued control "gain" parameter $(0 \le \alpha \le 1)$. This control can be implemented according to a fixed sampling rate or according to a variable sampling rate. For this research the control was updated at a variable rate after sufficient time for the estimation and actuation to occur. $\hat{c}_k$ is an estimate of the influence coefficient obtained by measuring the change in vibration for a given change in balance correction and using the estimation formula

$$\hat{c}_k = (1-\beta)\hat{c}_{k-1} + \beta\left(\frac{e_k - e_{k-1}}{w_k - w_{k-1}}\right) \tag{3}$$

The real-valued β parameter $(0 \le \beta \le 1)$ is a "forgetting factor" for an exponentially weighted moving average estimation.

The estimation will "track" the actual influence coefficient c as it varies over time. For the case of a step change in the actual influence coefficient to a new constant value, the influence estimation convergence is governed by the expected value equation

$$E[\hat{c}_k] = c + (\hat{c}_0 - c)(1-\beta)^k \tag{4}$$

If the actual plant influence coefficient and the disturbance remain constant during control convergence, the adaptively controlled error response can be derived. This represents the typical machine tool scenario in which the machine dynamics may shift after a tool or spindle speed change but then will remain constant during the few seconds in which active balancing is subsequently performed.

We must also assume that "sufficient excitation" exists to allow non-singular estimation at each control iteration. Thus, when the control has converged well enough that the balance correction is no longer changing, the estimation must be "turned off. To analyze the adaptive control response during convergence, we can substitute the expected value of the influence coefficient estimate from (4) into the control law of (2). The adaptively controlled vibration error history can then be described by the product

$$e_{k+1} = e_0 \prod_{j=0}^{k}\left(1 - \frac{\alpha c}{c + (\hat{c}_0 - c)(1-\beta)^j}\right) \tag{5}$$

Regardless of the initial influence estimate $\hat{c}_0$, the argument of the infinite product of (5) converges (assuming sufficient excitation) in the limit such that:

$$\lim_{j\to\infty}\left(1 - \frac{\alpha c}{c + (\hat{c}_0 - c)(1-\beta)^j}\right) = 1 - \alpha \tag{6}$$

Because the control gain α is defined such that $0 < \alpha \le 1$, there will exist a control iteration *p* ($p < \infty$) such that when $j = p$ the magnitude of the argument will be less than one. Although the infinite product argument magnitude will eventually fall below one and thereafter cause the product to converge, the magnitude of e_k may continue to increase until the p^{th} iteration. The corresponding vibration e_p will reach the maximum value

$$e_p = e_0 \prod_{j=0}^{p-1}\left(1 - \frac{\alpha c}{c + (\hat{c}_0 - c)(1-\beta)^j}\right) \tag{7}$$

After the p^{th} iteration, the error magnitude will begin to decrease. Thus the magnitude of the error at the p^{th} iteration depends on the magnitude of the estimation error ($\hat{c}_0 - c$) and the value of β.

Because the iteration with maximum vibration error magnitude occurs before the infinite product argument converges to $1-\alpha$, the value *p* will always be finite. Therefore the maximum controlled error must be bounded. For any arbitrary finite value e_p and any complex term *r* such that $|r| < 1$, the infinite product shown in (8) will exponentially converge to zero as $k \to \infty$.

$$e_{k+1} = e_p \prod_{j=p}^{k} r \tag{8}$$

The significance of this result is that, assuming sufficient excitation and that the plant influence coefficient and disturbance remain constant during control convergence, the infinite product of (5), and hence the adaptive control law of (2), is stable *regardless of the initial influence coefficient estimate.*

The only caveat in the stability condition proven above is that since the actual influence coefficient is unknown, there is no way of telling how high the error signal will get before it begins to converge to zero. Choosing $\alpha = \beta = 1$ will cause faster adaptation and control convergence. However, the higher the value of α, the worse the temporary vibration error may become during estimation convergence. Thus, although the fixed-parameter adaptive control system is stable, an erroneous initial influence coefficient estimate will always present a trade-off between speed of control convergence, and the amount of temporarily high vibration "overshoot".

PARAMETER AUTO-TUNING ADAPTIVE CONTROL

Varying the adaptive parameters α and β during each control iteration can eliminate the trade-off between control convergence rate and worst case temporary vibration. When the influence estimate is accurate, a value of α close to unity would provide the most rapid control convergence. Otherwise, a low value of α provides more cautious control and thereby limits the worst case vibration error.

Although the actual influence coefficient during control is unknown, one can measure the convergence of the influence estimate by comparing the instantaneously measured value with the exponentially weighted averaged estimate. ε_k is defined as a normalized measure of estimation convergence error at iteration *k* such that

$$\varepsilon_k = \sqrt{\frac{\left(c_{new} - \hat{c}_{k-1}\right)^* \left(c_{new} - \hat{c}_{k-1}\right)}{\hat{c}_{k-1}^* \hat{c}_{k-1}}} \qquad (9)$$

where $c_{new} = \dfrac{e_k - e_{k-1}}{w_k - w_{k-1}}$ and $\hat{c}_{k-1}$ is defined in (3). Assuming that the actual influence coefficient and unbalance disturbance did not change during control convergence, this estimation convergence measure will be unbiased. That is, the parameter ε_k will eventually converge to zero as the influence estimate converges according to (4).

To implement the automatic adjustment of parameters α and β during each control iteration, the following functions are proposed.

$$\alpha_k = 1 - e^{\left(-1/\eta_\alpha \varepsilon_k\right)} \qquad (10)$$

$$\beta_k = e^{\left(-1/\eta_\beta \varepsilon_k\right)} \qquad (11)$$

where α_k and β_k are the control gain and estimation forgetting factors respectively to be used at each control iteration *k*. η_α and η_β are positive real scaling factors to allow flexibility in shaping the response of each parameter. (10) and (11) ensure that when the influence estimation convergence error is high, the control gain α_k is low, limiting the worst case vibration error. When estimation convergence error is low, the control gain α_k approaches unity, ensuring fast control convergence. Conversely, the estimation weighting parameter β_k is close to unity when estimation convergence error is high, ensuring fast estimation response. β_k is low when the estimation is more converged, reducing the effect of measurement noise. A very small positive real number can be added to the denominator in the exponents of (10) and (11) during computation to ensure numerical robustness.

Using the function for β_k given in (11), the auto-tuning influence estimation equation is given by

$$\hat{c}_k = \left(1 - \beta_k\right)\hat{c}_{k-1} + \beta_k \left(\frac{e_k - e_{k-1}}{w_k - w_{k-1}}\right) \qquad (12)$$

The auto-tuning adaptive control law subsequently uses α_k given by (10) and $\hat{c}_k$ computed by (12) to update the control according to:

$$w_{k+1} = w_k - \alpha_k \frac{e_k}{\hat{c}_k} \qquad (13)$$

AUTOMATIC SUPERVISORY LIMIT SELECTION

A supervisory strategy allows coordination of the active balancing with the machine tool controller. The system is activated after a tool or spindle speed change and begins active balancing if vibration exceeds a certain threshold. After controlling vibration below a threshold, the system deactivates itself and signals the machine tool to begin machining. Such a strategy eliminates wear and tear on the balancer and machine tool likely to occur if balancing were attempted during metal cutting.

One should set activation thresholds as low as possible to ensure that low vibration levels are achieved. However, measurement noise, variation in machine dynamics and resolution limitations of the balance actuation device constrain just how low the vibration error can be controlled. Typical end users lack the special engineering knowledge to make these adjustments. Therefore, an automated method of selecting control limits is outlined here.

For active balancing devices with discrete states such as the one used for this research, the worst case correction resolution can be defined. This resolution, in combination with the estimate of the system influence coefficient, can be used to define the low vibration error limit at which control will "deactivate". This limit can be defined as

$$e_{low_k} = |\hat{c}_k| w_{res} e^{-\eta_e \varepsilon_k} \tag{14}$$

where w_{res} is the worst-case balance correction resolution, η_e is a unit-less positive real scaling factor added for flexibility in shaping response. The exponential term helps ensure that the control does not prematurely deactivate because of an erroneous influence coefficient estimate. When the influence coefficient estimation is converged (ε_k is small) the low control limit will be the vibration error expected at the worst case resolution.

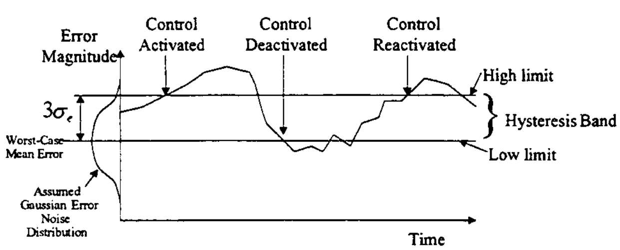

FIGURE 1. HYSTERESIS BAND BETWEEN THE SUPERVISORY LIMITS TO REDUCE SPURIOUS CONTROL ACTIVATION

To help prevent spurious control activation due to random noise, an additional "high" limit can be defined to incorporate a hysteresis band into the supervisory control. Thus once the control is deactivated when the vibration falls below the low limit, it is not reactivated unless the vibration exceeds the "high" limit as shown in Figure 1 and defined as

$$e_{high_k} = 3\sigma_e + e_{low_k} \tag{15}$$

where σ_e is the standard deviation of the vibration error magnitude measurement. This standard deviation can be continuously measured whenever the control system is deactivated and simply monitoring the idling spindle vibration error. Assuming that the measurement noise is Gaussian, even in the worst case when the error magnitude mean were stationary at the low limit, there would be a 99.7% probability that the noisy measured error signal would not exceed the high limit of (15) and spuriously activate the control.

By using (14) and (15) to automatically select supervisory control limits, no specialized user knowledge or user input is required. Furthermore, these automatic selection criteria take into account specific plant dynamics, active balance correction resolution and vibration error measurement noise.

EXPERIMENTAL RESULTS

To experimentally validate the auto-tuning control, an active balancing device was mounted on a grease-lubricated liquid-cooled 10 kW high-speed CBN grinding spindle and rotated at 20,000 rpm.

The active balancing device contained two unbalanced rotors that could be repositioned while the spindle rotated (Dyer et al., 1998). Permanent magnets locked the rotors in position when unpowered. The rotors were moved angularly using stationary electrical coils that generated magnetic flux across an air gap to the rotating portion of the device. Figure 2 shows the apparatus used in the control experiments.

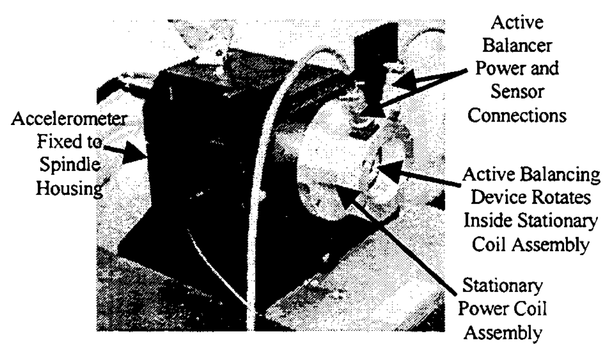

FIGURE 2. TEST SPINDLE USED FOR AUTOMATIC PARAMETER TUNING ADAPTIVE CONTROL EXPERIMENTS

The auto-tuning adaptive control was tested for various cases of unknown step changes in the unbalance disturbance and influence coefficient. The time required for each control iteration varied from 0.1 to 0.4 seconds depending on the balance actuation time and vibration measurement duration. Vibration was sampled at a faster rate of 32 times per spindle revolution.

Figure 3 shows the comparative results using an initial influence coefficient estimate approximately 180° out of phase with the actual influence coefficient. Aside from the raw vibration signals, Figure 3 also shows the corresponding filtered synchronous vibration error values and adaptive parameters during the control convergence. Note that the erroneous initial influence coefficient estimate caused both controllers to temporarily increase the vibration error magnitude. However, the auto-tuning controller limited the worst error magnitude to a much lower value while converging as fast, or even faster than the conventional adaptive controller.

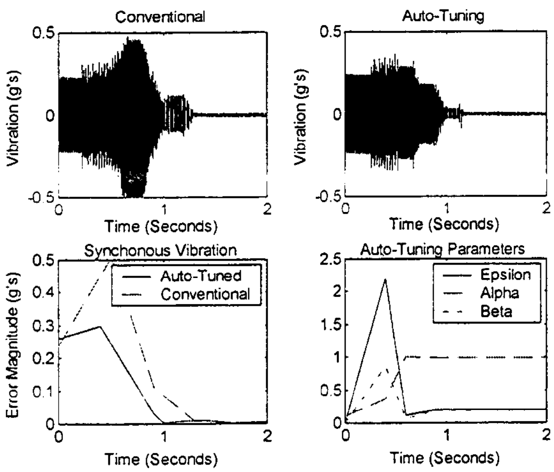

FIGURE 3. CONVENTIONAL FIXED-PARAMETER ($\alpha = 0.9, \beta = 0.8$) AND AUTO-TUNING ADAPTIVE CONTROL PERFORMANCE WITH ERRONEOUS INITIAL INFLUENCE ESTIMATE

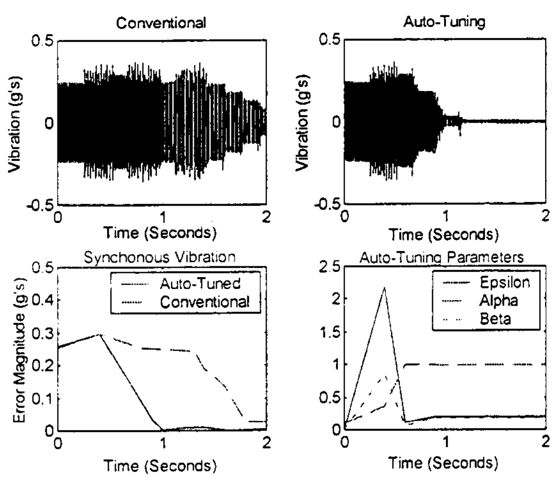

FIGURE 4. "CAUTIOUS" CONVENTIONAL FIXED-PARAMETER ($\alpha = 0.1, \beta = 0.8$) AND AUTO-TUNING ADAPTIVE CONTROL PERFORMANCE WITH ERRONEOUS INITIAL INFLUENCE ESTIMATES

The conventional control gain was then set to $\alpha = 0.1$ to limit the worst case error magnitude to that of the auto-tuning controller. Figure 4 shows that this "cautious" approach did in indeed limit the worst-case vibration. However, the convergence rate was significantly slowed compared to the auto-tuning control.

When the initial influence coefficient estimate was accurate, conventional adaptive control performance was typically very good. The worst case error was very low and control convergence was rapid. Figure 5 shows that the auto-tuning adaptive control also matched the conventional control performance when an accurate influence estimate was available.

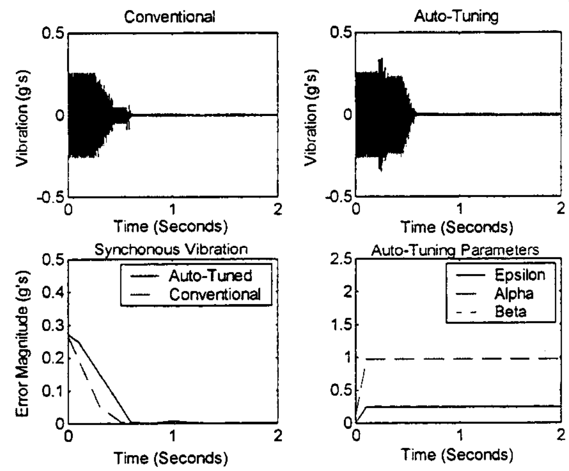

FIGURE 5. CONVENTIONAL ADAPTIVE CONTROL ($\alpha = 0.9, \beta = 0.8$) AND AUTO-TUNING CONTROL PERFORMANCE WITH ACCURATE INITIAL INFLUENCE ESTIMATES

The automatic supervisory limit selection method was enabled during the experimental testing. Figure 6 shows the automatically calculated supervisory limit settings from the experiment illustrated in Figure 3.

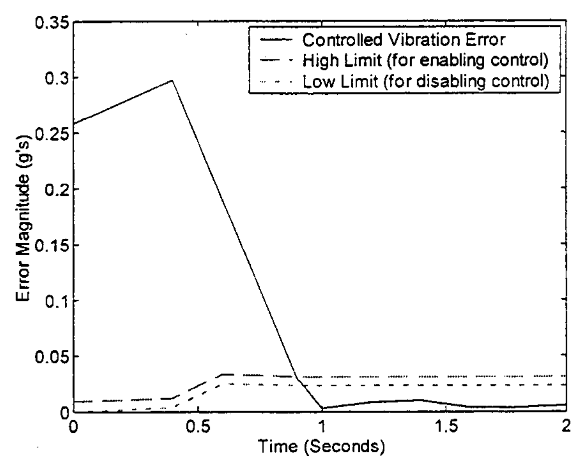

FIGURE 6. EXPERIMENTAL RESULTS USING AUTOMATIC SUPERVISORY CONTROL LIMIT SETTING WITH AUTO-TUNING ACTIVE BALANCING SYSTEM

Control was deactivated once vibration error magnitude was controlled below the low limit at about

1.0 seconds elapsed time. Control was never reactivated because vibration error magnitude never exceeded the high limit. The standard deviation of the vibration error magnitude measurement noise during this test was 0.0029 g's. The active balancing device used in the test had two stepper motor-type balance rotors each with 60 detent increments per revolution. The worst-case balance correction resolution for this configuration is π/n_{detents} (i.e., 5.2%) of the maximum balance correction capacity of the device.

SUMMARY AND CONCLUSIONS

The research presented here substantially eliminates performance trade-offs inherent in fixed-parameter adaptive control and automatically incorporates engineering knowledge to simplify the active balancing system operation for the end-user.

A stability analysis was presented for the fixed-parameter adaptive influence-coefficient control in the typical case where the synchronous disturbance and plant influence coefficient do not change during control convergence. The adaptive influence coefficient control was shown to be stable in these cases regardless of the initial influence coefficient estimate. However, the worst case temporary vibration during control adaptation could become quite large for erroneous influence coefficient estimates. A trade-off exists between speed of control convergence and the magnitude of this worst case error.

An automatic tuning method was therefore presented that allows the adaptive control parameters to be adjusted during each control iteration. The parameters were adjusted based on a measure of the influence coefficient estimation convergence. When estimation was not converged, the control became less aggressive and the estimation placed more weight on the instantaneously measured influence coefficient. When estimation convergence error was low, the adaptive parameters were adjusted to provide more aggressive control and to place more weight on the long-term averaged estimation.

This auto-tuning method limits the worst case error magnitude while still providing the same (or better) control convergence than conventional fixed-parameter adaptive control. Furthermore, because parameters are varied automatically during each control iteration, user setup for each individual machine or environmental condition is eliminated.

Supervisory control is necessary to "turn off" control so that machining operations can proceed once vibration is controlled below an acceptable limit. Significant specialized engineering knowledge is typically required to set supervisory vibration error limits for each application. Automatic supervisory limit selection criteria were defined to eliminate the need for such specialized end user input. The vibration error limits for enabling and disabling control were defined based on functions of machine dynamics, estimation convergence, active balance mass actuator resolution and vibration measurement noise.

Experimental results verified that the "auto-tuned" controller provided control response speed comparable to, or better than, the conventional adaptive control while maintaining significantly lower worst case vibration error magnitudes. The experiments also illustrated the effectiveness of the auto-tuning supervisory control with integrated automatic error limit calculation.

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