DISTURBANCE FEEDBACK TECHNIQUES FOR HYDROFOIL CRAFT USING ACCELERATION MEASUREMENTS

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Abstract: The paper describes a simple analytical framework to be used when designing control algorithms for systems of specific type – in which the state derivatives go in feedback as accelerometer signals, and the overall controller explicitly exhibits an algebraic disturbance feedback loop. A simplified hydrofoil craft linear model is treated as an example. The method proposed combines all the approaches based on the use of the simplified model and shows the purpose of acceleration feedback with respect to the hierarchy of control loops. Copyright © 2003 IFAC

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1. INTRODUCTION

In hydrofoil control, acceleration feedback (AF) is traditionally used for ride smoothing. The key idea is that a plant disturbance acting at the input of a mechanical plant impacts directly on its acceleration. Thus, it seems reasonable to use acceleration measurements to extract the disturbance components of the acceleration, and inject them directly at the plant input to counteract the effect of the disturbance. Another interpretation can be done in terms of the plant inertia. It is well known that the plant inertia (or effective mass) can be increased by AF (see, for instance, (Roskilly et al., 1996; Fossen et al., 2002)), and the closed-loop plant gets “heavier”. AF itself does not produce strictly positive effect. Simply adding an AF loop to a plant that possesses good properties will rather destroy them, and the response to disturbances will not be reduced. Therefore, the plant inertia must be increased only for disturbances. This needs some additional control loops. Only their combination with AF will provide a positive effect.

Thus, one should talk about developing AF into disturbance feedback (DF). Such a strategy looks attractive, because the problem of system stabilization and improving ride quality can be treated independently to a certain degree (Roskilly et al., 1996). We shall show later that there exist only two ways in which AF can be used as a component of algebraic DF loop. Nevertheless, there have been much more ideas on this way. The difference consisted in how a system designer interpreted the AF effect within the overall control structure. The variety of AF approaches was mostly caused by a common strategy of design where a controller was considered to be a combination of different loops with weakly crossed purposes (Lunde, 1993; Roskilly et al., 1996; Skorohodov et al., 1999; Skorohodov, 2000). Since such decomposition was interpreted in different ways, it caused the variety of solutions. A number of common misconceptions can be found in the literature and engineering practice, resulting from interpreting the AF effect in a wrong way. So, it would be important to consider a simplified model to find out how many AF approaches could be proposed for that model. In this paper, only the longitudinal control problem is considered. The main contribution of the paper is a unified scheme that clearly describes the purpose of AF with respect to the hierarchy of feedback loops. We discuss the concept of DF and show how it relates to traditional engineering
approaches. We show that the AF signal usually belongs to some DF signal, even if a system designer does not follow the concept of DF. Most of the topics discussed have not been addressed previously in the literature.

The paper is organized as follows. Section 2 describes a simplified 4th order model to be used throughout the paper. Section 3 introduces the DF method. Common misconceptions are discussed in Sections 3 and 4.

2. PLANT UNDER CONSIDERATION

In the longitudinal control problem, the craft lateral motions are negligible; only surge, heave and pitch equations need to be considered:

\[
\begin{align*}
\text{(surge)} & \quad X = m(u + qw), \\
\text{(heave)} & \quad Z = m(w - qu), \\
\text{(pitch)} & \quad M = I_y \dot{q},
\end{align*}
\]

where \(u\) and \(w\) are the velocities in the direction of the body-fixed \(x\) and \(z\) axes respectively; \(q\) is the angular velocity about the body-fixed \(y\) axis; \(X\) and \(Z\) are the scalar components of external force vector in the direction of the \(x\) and \(z\) axes respectively; \(M\) is the scalar component of external torque vector about the \(y\) axis; \(m\) is the mass; \(I_y\) is the moment of inertia about the body-fixed \(y\) axis (Roskilly et al., 1996). The coordinate frame is defined in accordance with (Fossen, 1994).

To explain main ideas, a simplified version of the above model will be treated. The aerodynamic lift generated by the hull and the slamming forces are neglected. The dynamics of sensors and actuators are neglected too. Furthermore, the ship velocity \(u\) is assumed to be constant. Thus, we restrict ourselves with a model of the 4th order (Ambrosovsky et al., 1995; Roskilly et al., 1996). (Note that the symbol \(u\) will be further used to denote the control signal.) The linearization of such a model will be treated throughout the paper:

\[\dot{x} = Ax + \xi + Bu\]  \hspace{1cm} \text{(1)}

where

\[
A = \begin{bmatrix}
0 & 1 & 0 & 0 \\
0 & 0 & 0 & 1 \\
a_{21} & a_{22} & a_{23} & a_{24} \\
a_{41} & a_{42} & a_{43} & a_{44}
\end{bmatrix}, \quad B = \begin{bmatrix}
0 & 0 \\
0 & 0 \\
b_{21} & b_{22} \\
b_{41} & b_{42}
\end{bmatrix}.
\]

The state is \(x = [z \ w \ \theta \ q]^T\), the control is \(u = [u_1 \ u_2]^T\), where \(z\) is the position of the center of gravity in the \(z\)-direction, \(w = z\), \(\theta\) is the pitch angle, \(q = \dot{\theta}\), \(u_1\) and \(u_2\) are the flap angles \(\delta_1\) and \(\delta_2\) respectively (Fig.1). The disturbance is \(\xi = [0 \ \xi_1 \ 0 \ \xi_2]^T\): its components \(\xi_1\) and \(\xi_2\) correspond to the vertical force in the center of gravity and moment about the body-fixed \(y\) axis respectively.

![Figure 1](image)

The approach discussed is based on the properties of the simplified model. First, the 1st and 3rd rows in (1) have zero coefficients at the disturbance and control. Therefore, we can restrict ourselves with the consideration of the \(T\)-projection of (1), i.e.

\[\dot{T}_x = T_\xi + T_u\]

where \(T = \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}\). Second, the matrix \(T_b = \begin{bmatrix} b_{21} & b_{22} \\ b_{41} & b_{42} \end{bmatrix}\) is nonsingular since \(\text{sign}(b_{21}) = \text{sign}(b_{22})\) and \(\text{sign}(b_{41}) = -\text{sign}(b_{42})\).

Third, the signal \(T_\xi = \begin{bmatrix} w \\ \dot{q} \end{bmatrix}\) can be measured via the accelerometer signals \(a_1\) and \(a_2\) since \(T_\xi = L^{-1}a\), where \(a = [a_1 \ a_2]^T\) and the matrix \(L = \begin{bmatrix} 1 & -L_1 \\ 1 & -L_2 \end{bmatrix}\) is nonsingular (we always assume that \(L_1 \neq L_2\)). Finally, we prefer to consider the disturbance signal \(T_\xi = [\xi_1 \ \xi_2]^T\) instead of \(\xi\). Obviously that \(\xi = B_\xi T_\xi\), where

\[
B_\xi = \begin{bmatrix}
0 & 0 \\
1 & 0 \\
0 & 0 \\
0 & 1
\end{bmatrix},
\]

and that \(B_\xi = B(TB)^{-1}\). Taking the above into consideration, the equation (1) can be rewritten as

\[\dot{x} = Ax + B_\xi T_\xi + Bu\]  \hspace{1cm} \text{(2)}

3. DISTURBANCE FEEDBACK

The behavior of a linear plant is a sum of its zero-input response and responses to external signals (disturbance and command signal). By definition, the DF signal \(u_{df}\) influences only the plant response to disturbance. Write the plant equation as

\[y(s) = G(s)(TB)^{-1}T_\xi(s) + G(s)u(s)\]

where \(y = [z \ \theta]^T\) is the plant output,

\[G(s) = C(sI - A)^{-1}B\]

and \(C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 \end{bmatrix}\). When
examining the plant (2), we find two ways to implement the algebraic DF loop $u_{df}$:

- $T_\xi^-$-feedback
  
  \[ G(s)(TB)^{-1}T_\xi(s) + G(s)u_{df}(s) = \]
  
  \[ = G(s)(TB)^{-1}\eta T_\xi(s) \]

- $y^{(d)}$-feedback
  
  \[ G(s)(TB)^{-1}T_\xi(s) + G(s)u_{df}(s) = \]
  
  \[ = \eta G(s)(TB)^{-1}T_\xi(s) \]

Here $\eta$ is a nonsingular $2\times2$-matrix. (In general, we should consider $\eta$ to be a matrix transfer function, to obtain a frequency dependent DF gain.) Obviously that both the structures are the same in the sense of the plant response if

\[ G(s)(TB)^{-1}\eta = \eta G(s)(TB)^{-1} \]

(for instance, if $\eta$ is a scalar).

### 3.1 $T_\xi^-$-feedback

This kind of DF loop closely relates to the inertia shaping technique and assumes the use of the following control structure

\[ u = u_\ast + K_a a, \]

where $K_a$ is a $2\times2$ matrix and $u_\ast$ is an arbitrary control loop. For simplicity, we assume that $u_\ast$ does not contain $Tx$-terms. The signal $u_\ast$ usually includes a state feedback (SF) and an integral feedback (Johnson, 1985; Yamato et al., 1998; Skorohodov, 2000). Applying the controller (3) to the plant (2) yields

\[ E\dot{x} = Ax + B_2 T_\xi + Bu_\ast, \]

(4)

since $a = LT\dot{x}$. If $\det(I - TBK_a) = 0$ then $E$ is singular. (The symbol $I$ denotes a unity matrix.) This situation is of no particular interest, for in all practical systems it is not the case. So, we always assume $K_a$ to be chosen so that

\[ \det(I - TBK_a) \neq 0 \]

Rewrite (4) as

\[ \dot{x} = \tilde{A}x + \tilde{B}_2 T_\xi + \tilde{B}u_\ast. \]

The loop $u_\ast$ will be designed for a “new” plant whose inertia has been changed by applying the AF loop. In this situation, it would be much more suitable to consider the controller (3) to be a combination of two signals $u_b$ and $u_{df}$, i.e. $u = u_b + u_{df}$, where $u_b$ is such that $Ax + Bu_b = \tilde{A}x + \tilde{B}u_\ast$, while $u_{df}$ provides the transformation $B_2 \rightarrow \tilde{B}_2$. The signal $u_b$ provides stability, command tracking and the plant response to the “reduced” disturbance $\tilde{B}_2 T_\xi$. Notice that we allow each of the signals $u_b$ and $u_{df}$ to be virtual (i.e. possible not physically realizable); however we always demand the physical realization for the sum of these signals. Therefore, let us show that each pair $(u_\ast, K_a)$ can be described as a pair $(u_b, u_{df})$.

**Definition.** If the control signal $u$ can be decomposed as $u = u_b + u_{df}$, so that

\[ B_2 T_\xi + B(u_b + u_{df}) = B_\eta T_\xi + Bu_b \]

where $\eta$ is non-singular, then the signal $u_b$ is referred to as the basic loop, while the signal $u_{df}$ is referred to as the $T_\xi^-$-feedback loop.

It is easy to check that

\[ u_{df} = (TB)^{-1}(\eta - I)T_\xi. \]

If $T_\xi = 0$ then $u_{df} = 0$ and $u = u_b$. Strictly speaking, the signal $u_{df}$ should be interpreted as

\[ u_{df} = \frac{(TB)^{-1}(I - \eta^{-1})\cdot \eta T_\xi}{\Omega} \]

where $\Omega$ is the DF gain.

**Proposition.** If (5) holds then the plant

\[
\begin{align*}
\dot{x} & = Ax + B_2 T_\xi + Bu \\
0 & = u_\ast + K_a a
\end{align*}
\]

can be written as

\[
\begin{align*}
\dot{x} & = Ax + B_2 T_\xi + Bu_b \\
u & = u_b + (TB)^{-1}(I - \eta^{-1})T_\xi \quad u_{df}
\end{align*}
\]

(7)

where $\eta = (I - TBK_a L)^{-1}$ and

\[ u_b = (TB)^{-1}(I - \eta^{-1})T_\xi L^{-1}a - \eta T_\xi - \eta TBu_\ast, \]

(8)

The signal $K_a a$ is a component of the signal $u_{df}$.

**Proof.** It is easy to check that both the signals (8) and (9) satisfy the above Definition, and the sum of (8) and (9) equals (3). It is also clear that the signal

\[ (TB)^{-1}(I - \eta^{-1})L^{-1}a \]

belongs to $u_{df}$.

Introduce the signal $\Phi_{df}$ by the relation

\[ \Phi_{df} + K_a a = u_{df}, \]

that is

\[ u = u_b + \Phi_{df} + K_a a = u_b + \Phi_{df} + K_a a. \]

Simple calculation shows that

\[ \Phi_{df} = (TB)^{-1}(I - \eta^{-1})(-\eta T_\xi - \eta TBu_\ast). \]

The signal $\Phi_{df}$ develops AF into DF with respect to $u_b$. In the above Proposition, we do not demand the state to be measurable; also the signal $u_\ast$ is not assumed to include a SF component. For instance, let $u = K_a a$. In this case

\[ u_b = (TB)^{-1}(I - \eta^{-1})TAx, \]

\[ u_{df} = (TB)^{-1}(I - \eta^{-1})(L^{-1}a - \eta T_\xi), \]

so $u_b + u_{df} = K_a a$, and the overall SF signal is zero. But the overall control signal includes two virtual SF signals: $(TB)^{-1}(\eta - I)TAx$ and $-(TB)^{-1}(\eta - I)TAx$, respectively.
the former belonging to \( u_b \) and the latter to \( \Phi_{df} \).

The above Proposition shows that, dealing with the structure (3), one has the only way to use AF – via the corresponding DF loop. Therefore, one would design the controller (3) in terms of \( u_b \) and \( u_{df} \). Assume the signal \( u_b \) is given and physically realizable. The value of \( \eta \) with \( \det \eta \neq 0 \) is assumed to be known. Our goal is to find the signal \( u_{df} \). First, write \( T_\xi \) as
\[
T_\xi = T \bar{x} - T A \bar{x} - T B u_b - T B u_{df} .
\]
Then, taking (6) into account we obtain
\[
\begin{align*}
\begin{aligned}
\dot{u}_{df} &= (TB)^{-1}(I - \eta^{-1}) \left( L^{-1}_a \bar{x} - T A \bar{x} - T B u_b \right) \\
\end{aligned}
\end{align*}
\]

(10)
The overall controller is
\[
u = (I - \Omega T B) u_b + \Omega L^{-1} a - \Omega T A \bar{x} .
\]

Also, note that there are two particular cases where only one accelerometer is needed:
\begin{itemize}
\item \( \eta = \text{diag}(\eta_1, 1) \) which corresponds to \( \xi_1 \) feedback and involves the 2nd equation in (1);
\item \( \eta = \text{diag}(1, \eta_2) \) which corresponds to \( \xi_2 \) feedback and involves the 4th equation.
\end{itemize}

There are some issues to keep in mind:
\begin{itemize}
\item The AF signal produces the DF signal and gets its component. All the properties of the AF loop are enclosed into the corresponding DF loop. The signal (10) includes an “observer” of the signal \( \eta T_\xi \). The “observer” is based on the plant equation. If the signal \( u_{df} \) is virtual the “observer” is virtual too.
\item Assume, we are given two controllers
\[
\begin{align*}
\begin{aligned}
\dot{u}_1^{(1)} &= u_1^{(1)} + K_a a \\
\dot{u}_2^{(1)} &= u_2^{(1)} + K_a a
\end{aligned}
\end{align*}
\]
and
\[
\begin{align*}
\begin{aligned}
\dot{u}_1^{(2)} &= u_1^{(2)} + K_a a \\
\dot{u}_2^{(2)} &= u_2^{(2)} + K_a a
\end{aligned}
\end{align*}
\]
where \( u_1^{(1)} \neq u_1^{(2)} \). Clearly that \( u_1^{(1)} \neq u_2^{(2)} \). However, from the above Proposition it follows that the DF signal is the same in both the controllers, i.e. \( u_1^{(1)} = u_2^{(2)} \) and \( u_1^{(1)} = u_2^{(2)} \). Important to notice that, although \( u_1^{(1)} = u_2^{(2)} \) implies \( K_a a + \Phi_{df}^{(1)} = K_a a + \Phi_{df}^{(2)} \), however the signal \( a \) in \( u_1^{(1)} \) differs from the signal \( a \) in \( u_2^{(2)} \), as well as \( \Phi_{df}^{(1)} \) differs from \( \Phi_{df}^{(2)} \).
\item If \( u_{df} \) is physically realizable then \( u_{df} \) must be realizable too. In this case the use of SF cannot be avoided. Indeed, from (10) it follows that \( u_b = 0 \) implies \( u_{df} = \Omega L^{-1} a - \Omega T A \bar{x} \). This is the minimal structure of the DF loop. Thus, developing AF into DF requires the signal \( \Phi_{df} \) which certainly includes a SF component. AF is very far from DF, because \( K_a \) large implies \( \Phi_{df} \) large, even if \( u_a = 0 \).
\item There have been many AF approaches based on the control structure (3). From the above Proposition it follows that two different AF approaches differ only in what pair \( (u_b, \eta) \) each of them assumes.
\end{itemize}

- The plant response to the disturbance \( T_\xi \) is
\[
W_b(s) \eta T_\xi(s) \quad \text{(11)}
\]
where \( W_b(s) \) is the matrix transfer function of the plant closed with the loop \( u_b \), from the “reduced” disturbance \( \eta T_\xi \) to the plant output \( y \). Since \( W_b(s) \) in (11) is not diagonal, the plant response to the signal \( u_{df} \) will be in both the heave and pitch motions, even if \( \eta \) is diagonal. Hence the \( T_\xi \)-feedback loop does not satisfy the concept of height and pitch control channels.

AF itself is not effective unless it properly develops into DF. This is illustrated in Fig. 2. The signal \( u_\ast \) is assumed to be chosen and provide good performance (Fig. 2.a). Our purpose is to develop this controller so that the plant response to disturbances is reduced. Fig. 2.b shows how to solve this problem by adding the DF loop. In this case we consider \( u_\ast \) as \( u_b \) and add the appropriate signal \( K_a a + \Phi_{df} \) which is the DF signal with respect to \( u_b = u_\ast \). Fig. 2.c illustrates one of misconceptions, where a system designer tried to reduce the plant response to disturbances by simply adding the AF loop. In this case the DF signal is the same; however, the basic loop is not the same.

Following this way (Fig 2.c) causes the flap overloading and poor stability, but the plant response to disturbances is not reduced. Such a mistake was found in (Chernyshova et al., 1996; Skorohodov, 2000), where an optimal value for \( K_a \) was proposed, without any consideration what signal \( u_\ast \) should be (see the details in (Runyantsel, 2003)).

3.2. Controller optimization problem

The controller optimization problem consists in the optimization of the pair \( (u_b, \eta) \) for the plant (7), while the pair \( (u_\ast, K_a) \) relates to the controller implementation. A model from (Ambrosovsky et al., 1995) has been tested. DF worked well, but it did not provide absolute advantages. Some reasons have been found to choose the signal \( u_{df} \) small compared to the signal \( u_b \). First, the larger \( u_{df} \) is the smaller \( u_b \) will be, since the control power is limited. However, the signal \( u_b \) provides stability and command tracking,
hence it must be powerful enough. Second, the signal $u_b$ itself works well in the sense of reducing the plant response to disturbances. The larger $u_b$, the smaller gain $W_b(s)$ would be achieved. It is a reason to reduce the response to the disturbance by means of $u_b$, not $u_{df}$. Third, the value of $\eta$ cannot be chosen small because it results in a large value for $\Omega$, which may lead to insufficient robustness. Moreover, the signal $u_{df}$ causes the disproportional flap load. Thus, in our tests the signal $u_{df}$ was not recommended to be large. Notice that in (O’Neil, 1991) it has been found that the use of AF is crucial in order to reduce seaway-induced motion. However, such a conclusion was drawn for a SISO-plant (“a half of ship”), whereas in reality we deal with a MIMO plant.

**Example.** The concept of DF allows to reduce the plant response to disturbances without affecting the plant stability and response to the command signal. Theoretically, it looks very attractive. However, in reality we should take various criteria into consideration. Assume, we are given the plant

$$\dot{x} = Ax + B_2\xi + BK^{(0)}x,$$

and we are satisfied with the pole placement provided by $A + BK^{(0)}$. But we are not completely satisfied with the plant response to the disturbance, i.e. the signal $C(I - A - BK^{(0)})^{-1}B_2\xi(s)$ seems to be too large. Consider two ways to reduce this signal.

First, compute a new value $K^{(1)}$ for the state feedback gain. The signal $C(I - A - BK^{(1)})^{-1}B_2\xi(s)$ is small, however, the initial pole placement is perturbed. Second, add the DF loop with some value for $\eta$. The overall controller is

$$u = K^{(0)}x + K_\Phi x + K_\delta a = (K^{(0)} + K_\Phi)x + K_\delta a.$$  

The response to the disturbance is $C(I - A - BK^{(0)})^{-1}B_2\xi(s)$, and the initial pole placement is kept. Which way to prefer? Tests show that the second way requires more control power (Fig. 3).

![Diagram showing plant response to the signal $T_2$.](image)

Figure 3

As to the first way, the difference between $K^{(1)}$ and $K^{(0)}$ is not very large. Although not ideal, the pole placement provided by $A + BK^{(1)}$ might not be very bad.

3.3. $y^{(d)}$-feedback

It is easy to check that the $y^{(d)}$-feedback loop is

$$u_{df}(s) = G^{-1}(s)(I - \eta^{-1})\left(y(s) - G(s)u_b(s)\right)$$  

The DF loop (12) is designed in terms of the plant response to the disturbance; therefore, the concept of height and pitch control channels is realizable. Indeed, to do that we simply choose $\eta = \text{diag}(\eta_1, \eta_2)$. Important to notice, the DF signal is invariant to the use of a pre-compensator. This fact is sometimes ignored. An example was found in (Roskilly et al., 1996) where an approach is proposed to implement the DF signal in the height control channel. The approach is based on the assumption that the $4^{th}$ order plant can be decoupled into two $2^{nd}$ order SISO plants, each of them with a scalar control and scalar disturbance. We consider that methodology to be incorrect, and suggest another point of view. To implement the signal (12), $G^{-1}(s)$ must be realizable. Denoting by $P(s)$ the pre-compensator transfer function and considering a “new” control signal $v(s)$, so that

$$u(s) = P(s)v(s) = P(s)(v_b(s) + v_{df}(s)),$$

we obtain

$$y(s) = G(s)(TB)^{-1}\xi\xi(s) + G(s)P(s)v_b(s) + v_{df}(s)$$

It is easy to check that

$$v_{df}(s) = (G(s)P(s))^{-1}(I - \eta^{-1})y(s) - (G(s)P(s))^{-1}(I - \eta^{-1})G(s)P(s)v_b(s).$$

Following (Roskilly et al., 1996), let us choose $P(s)$ so that it eliminates the off diagonal terms in the plant transfer function matrix:

$$G(s)P(s) = \begin{bmatrix} \beta_1(s) & 0 \\ 0 & \beta_2(s) \end{bmatrix},$$

where both $\beta_1(s)$ and $\beta_2(s)$ are of the structure

$$\beta_i(s) = \frac{k}{\xi_i^2 + c_i^2}, i = 1, 2.$$  

(13)

Let us finally choose $\eta = \text{diag}(\eta_1, \eta_2)$. Then

$$v_{df}(s) = \begin{bmatrix} (1 - \eta_1^{-1})\beta_1^{-1}(s) & 0 \\ 0 & (1 - \eta_2^{-1})\beta_2^{-1}(s) \end{bmatrix} \begin{bmatrix} z(s) \\ \theta(s) \end{bmatrix}$$

Taking (13) into consideration, it becomes obvious that $\dot{z}$ and $\dot{\theta}$ are needed to implement $v_{df}(s)$. The controller proposed in (Roskilly et al., 1996) is a particular case of the above scheme with $\eta = \text{diag}(\eta_1, 1)$ (only one accelerometer was used). The only reason of using the pre-compensator is that it simplifies the realization of $G^{-1}(s)$. Furthermore, in (Roskilly et al., 1996) each of the $2^{nd}$ order plants uses the PDF control scheme (pseudo-derivative feedback), because “it makes less demands on the actuator than a
PI or PID controller”. That is not correct. Each of the 2nd order “plants” deals with the virtual signals $v_1$ and $v_2$ respectively, whereas the actuators’ activity is expressed in terms of the signals $u_1$ and $u_2$. Since $P(s)$ is not diagonal, the overall control signal $u(s) = P(s)v(s)$ is multivariable.

3.5. Filtering the accelerometer signal

The accelerometer signal must be filtered to avoid high frequency noise and instability induced in the real-time implementation. Strictly speaking, filtering should be applied to the entire DF signal. Therefore, $\eta$ and $\Omega$ become frequency dependent. The easiest way is to use $\eta = f_\eta(s)\tilde{\eta}$ where $\tilde{\eta}$ is a real nonsingular $2 \times 2$-matrix, $f_\eta(s)$ is a scalar transfer function, and $1 - (f_\eta(s)\tilde{\eta})^{-1}$ is proper and stable.

4. QUASI-LOCAL STRATEGY

In Fig.1, $\Delta Z_1$ and $\Delta Z_2$ denote the variations of lift forces at the foils. Denote by $\Delta Z_1^{(1)}$ and $\Delta Z_2^{(1)}$ the lift forces due to waves. Clearly that $(\Delta Z_1, \Delta Z_2)$-feedback is similar to AF, while $(\Delta Z_1^{(1)}, \Delta Z_2^{(1)})$-feedback is similar to $T_\xi\cdot$-feedback (through a nonsingular transformation). We have shown that $T_\xi\cdot$-feedback does not satisfy the concept of height and pitch control channels. In the similar manner, $(\Delta Z_1^{(2)}, \Delta Z_2^{(2)})$-feedback does not satisfy the concept of isolated foil control. Nevertheless, most of AF approaches were based on a quasi-local strategy where an accelerometer was placed above each foil trying to cancel out the vertical acceleration for the corresponding foil (see comments in (Lunde, 1993)). The quasi-local strategy assumes

$$u_{df} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \Delta Z_1^{(1)} \\ \Delta Z_2^{(1)} \end{bmatrix}$$

where $k_1 \geq 0$, $k_2 \geq 0$. But this strategy does not correspond to reality. Write down the transfer function from $u_{df}$ to $\begin{bmatrix} z_{1,f} \\ z_{2,f} \end{bmatrix}$, where $z_{1,f}$ and $z_{2,f}$ are the vertical coordinates of the fore and aft foils respectively. (We mean the transfer function for the plant closed with $u_{th}$.) This transfer function is not diagonal, i.e. each foil action influences the response in the others (Rumyantsev, 2003).

5. CONCLUSION

A unified framework for the use of AF was proposed, based on the properties of the simplified model. The above scheme covers most of the AF approaches that have appeared in the literature and engineering practice. Typical misconceptions have been outlined, resulted from attempts to solve the control problem in terms of reduced order plants. Most of the AF approaches are restricted to achieving only some particular effects that AF can provide. Because of the variety of solutions, the problem of controller optimization has not been properly posed. This problem is a subject of further research.

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REFERENCES


