Modeling and Requirements Formulation for Submarine Control Surface Actuation Systems

Raul G. Longoria, Jonathan LeSage, William Shutt

April 25, 2010

Abstract

This paper examines methods that can be adopted in early stage or retrofit design of actuator subsystems, and is motivated by the modern trend toward retrofitting legacy hydraulic actuation of submarine control surfaces with electromechanical systems. This problem highlights the familiar need designers have to relate system response requirements to selected subsystems to enable focused development of the latter. This paper shows the utility of adopting a model basis, and specifically uses a bond graph approach in combination with two-port immittance relations. Bond graphs benefit study of multidisciplinary systems and provide insight into system interconnection and causality. In combination with bond graphs, immittance functions enable key relations to be established based on the overall system description, and provide a way to specify response requirements. Imittance functions also enable adopting network synthesis methods, which are used in this paper to show how passive and active compensation can be integrated to benefit proposed actuation schemes. It is shown how this combination of methods provides designers with a systematic way of relating system response requirements to targeted subsystems. The methods described are demonstrated using a simplified control surface actuation problem, and simulation results of key static and dynamic requirements are presented. The derived passive and active compensation are used to augment conventional feedback controlled actuator models, and simulations demonstrate how compensation can reduce energy consumed by actuation subsystems.

*Manuscript originally submitted December 1, 2009. Final draft submitted April 25, 2010. This work was supported by the Office of Naval Research through the Electric Ship Research and Development Consortium.

†Corresponding author, R. Longoria is with the University of Texas, Department of Mechanical Engineering, 1 University Station C2200, Austin, TX 78712 USA (phone 512-471-0530, fax 512-471-8727, email: r.longoria@mail.utexas.edu).

‡J. LeSage is a graduate student at the University of Texas, Austin, TX USA.

§W. Shutt is with the University of Texas, Applied Research Laboratories, 1 University Station F0252, Austin, TX 78712 USA.
Introduction

This paper is motivated by an ongoing effort to retrofit submarine control surface actuators with electromechanical systems, replacing use of hydraulic systems that have been in service since World War II. Control surface actuation for shipboard systems has relied heavily on hydromechanical systems, taking advantage of legacy design knowledge. Further justification for continued deployment of these systems is the relatively high power density of hydraulics which can often outweigh drawbacks associated with maintainability. Nevertheless, retrofitting with electromechanical systems is motivated by electrification of shipboard systems, which promises improvements in actuation systems and resolution of problems associated with deploying hydraulics.

Actuator retrofit is a common problem, and this paper addresses needs for methods to aid formulation of requirements for actuation subsystems that correspond to submarine operational requirements. Modern modeling and simulation tools enable a total systems approach for this purpose which allows the possibility to propagate overall system response requirements into specified subsystems. However, early or concept design applications require that physics-based models be developed with minimal design information. Further, detailed selection and sizing depend on requirements, so it can be helpful to have systematic ways to model and simulate systems for gaining insight during this process.

This paper demonstrates part of the retrofit process concerned with modeling and requirements formulation, taking by example a submarine control surface actuator application. A sternplane control surface on a submarine is illustrated by Figure 1(a). The actuation system is represented for the purposes of this paper using a two-port rotational actuator system in (b), inserted between the moving ship base and the control surface inertia. In this way, it is recognized that the actuator system provides torque across an angular velocity difference defined by the ship and control surface motions. Practical control surface actuation systems achieve this function using complex mechanisms, traditionally employing hydraulic rams contained within the pressure hull. For the purposes of this paper, it is sufficient to consider the system illustrated in Figure 1. It is recognized that the final actuator, mechanical transmission, and packaging configuration requires detailed development. The methods reported in this paper are meant to support the early stages of retrofitting actuator systems, supporting related work such as that described for a shipboard actuator by Stafford and Osborne (2008).

The design and/or selection of an actuation scheme assumes that requirements have been defined and specifications formulated, critical steps that benefit from expert and/or institutional knowledge. Any deficit in this knowledge combined with changes in design or a need for technology insertion can benefit from modeling and simulation in the early design process. Models also help to capture design and facilitate system-level analysis that can be used to support design decisions. For example, established models of submarine dynamics (Gertler
(a) Sternplane control surface deflection and flow-induced disturbance torque. (b) A simplified model with insertion of two-port rotational actuator.

and Hagan, 1967) can be used as the basis for understanding and generating operational requirements for control surfaces, provided information on duty cycles exists. A model basis can also help relate control surface response requirements to actuation system requirements. Establishing complete actuation system requirements (operational, performance, environmental) is a precursor to development or selection of a specific actuator system. Aiding formulation of the operational requirements (e.g., duty cycle, peak levels, etc.) in particular is a main concern of this paper, as these can be related to dynamic system representations.

A direct way to derive actuator system requirements is by using a physics-based model. The case of a single actuator coupled directly to a load (inertia, external forces/torques, etc.) should meet force or torque requirements for a prescribed motion profile, and these are derived either analytically, by simulation, or through testing. Uncertainty arises in many ways, notably through the external forces, and in some applications the model basis can become very complex, especially when a system is comprised of multiple actuators. Additional complications arise because there can be several requirements that need to be satisfied, in which case it is necessary to decide whether a given actuator should have means for satisfying all the requirements, or if alternative/redundant actuation is required. Because of the varied applications where these types of problems arise, there are no commonly accepted analysis and design tools used to support engineers in dealing either with early stage design or retrofit of actuator subsystems. The need to deal with these problems on a case-by-case basis is not unheard of, and unnecessary cost and risk is introduced into the retrofit process.

This paper examines the actuator retrofit problem and the feasibility of supporting requirements generation using a model-basis supported with network synthesis techniques. Network synthesis involves mathematical tools used to derive networks from a specified performance characteristic. In electrical circuits, and by extension to other physical systems, the performance characteristic commonly takes the form of a transfer function or functions relating key response variables to inputs to a system. Transfer functions are a useful way to represent system response requirements. An extensive knowledge base exists for designing both passive
and active circuits which may have utility in other fields beyond electrical circuits, as recently reported by Smith (2002) and Connolly and Longoria (2009). This paper shows how semi-analytical methods based on immittance-based (impedance, immittance) synthesis methods can be used to represent (model) candidate designs for actuator subsystems. A methodology is described for deriving actuator subsystem requirements for submarine control surfaces, as a case study to describe how these techniques can be practically applied. It is assumed that the reader has some knowledge of basic system dynamics concepts (Karnopp et al., 2001). Lastly, these methods support a critical evolution in shipboard actuation systems as described by Tesar and Krishnamoorthy (2008).

Model-Basis for Actuator Requirements

A key requirement for the unknown actuation system in Figure 1(b) is the torque needed to provide controlled deflection of the control surface while rejecting disturbances. A conventional (direct) approach for determining this torque is to model a feedback-controlled ideal torque source applied between the base motion and the control surface drive shaft. Integrating this ideal actuator model within a model-based system analysis enables torque to be determined as a function of required control surface motions, submarine response, and modeled disturbances. A controller must be designed sufficiently robust to enable control during basic positioning of the control surface, emergency maneuvers (large deflection), and disturbance rejection. The results would provide insight into the torque-speed, power, and energy requirements for a torque actuator.

Figure 2: (a) Electrical two-port. (b) Generalized (multi-disciplinary) two-port with bonds conveying power, $P_i = e_i^f_i$. (c) Schematic for basic two-port rotary actuator.

An alternative approach proposed for deriving requirements begins with methods derived from network synthesis. Network synthesis methods have traditionally been used to generate preliminary designs based on a desired system response, usually expressed in the form of an immittance (impedance or admittance) transfer function between two variables of interest. Immittance-based synthesis methods developed for electrical networks are also applicable to
multidisciplinary systems (Hanish, 1985; Redfield and Krishnan, 1993; Smith, 2002), including certain types of actuation subsystems (Connolly and Longoria, 2009) as well as two-port systems (Kim, 2003). Two-port element models are especially well-suited for representing actuation systems, as shown in Figure 1(b), that have power flowing at two different ports (terminals). This concept is depicted as an electrical model in Figure 2(a), for the generalized case in (b) using bond graphs (Karnopp et al., 2001), and schematically for a rotary actuator in (c).

An electrical analog representation for the ideal torque source, \( T_a(t) \), is shown in Figure 3(a). The ideal torque can be replaced by an active impedance, \( Z_a(s) \equiv T_a/\omega_a \), as illustrated in Figure 3(b) as electrical analog or as equivalent bond graph form (c). A synthesis problem seeks to find this unknown impedance function in terms of system response requirements, which may be purely passive, purely active, or a combination. There are generally multiple solutions for synthesis problems, so the number of possible outcomes is reduced in this case by constraining the unknown impedance so it is connected in the same way as the ideal torque source (in shunt or parallel).

The unknown actuation system is represented as an active impedance, \( Z_a(s) \) and inserted as part of a two-port system into a known model of the sternplane control surface system, shown in Figure 4. For the purposes of this paper, this model assumes the actuation system will couple into rotational inertia, \( J_2 \), which is connected to the control surface by a drive shaft having stiffness, \( K \). On each end of the drive shaft, bearing losses are initially accounted for by linear frictional damping coefficients \( B_1 \) and \( B_2 \). The control surface is represented by a single rotational inertia having moment of inertia, \( J_s \). This overall model enables synthesis methods to be applied so that desired overall performance of the control surface system can be considered. In subsequent work, nonlinear effects can be readily incorporated into this model-basis.

The assumed topology (connectivity) actually restricts the possible solutions so that the impedance matrix has only a single impedance transfer function in a 2-by-2 matrix; i.e., it
can be shown that,

\[
\begin{bmatrix}
    T_1 \\
    \omega_1 \\
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\
    Y_a(s) & 1 \end{bmatrix} \begin{bmatrix} T_2 \\
    \omega_2 \end{bmatrix}
\]  

where admittance \( Y_a(s) = 1/Z_a(s) \). The search for alternative designs may use a more generalized two-port description as described by Kim (2003), however for this case study it is more useful and practical to impose this restricted form. Given the structure of this unknown two-port impedance matrix, the actuation impedance function can be integrated into the control surface system, and the overall model is shown in a bond graph in Figure 5. The individual elements in this bond graph are impedance elements, so it is also possible to adopt an impedance-based network (electrical analog) to convey the system element interconnections (topology). The reader unfamiliar with bond graphs should interpret the lines with half-arrows as power flow interactions, and the ‘1’ and ‘0’ nodes as physical junctions that have common flow and effort, respectively (e.g., like a series or parallel circuit connection). In general, bond graphs enable nonlinear, multi-port modeling, and the orthogonal lines on the power bonds represent signal causality. These are useful tools that the interested reader can find discussed in the text by Karnopp et al. (2001).

Using the system bond graph and the transmission matrices at each junction, the relationship between the input and output ports are found from,

\[
\begin{bmatrix}
    T_1 \\
    \omega_1 \\
\end{bmatrix} = \begin{bmatrix} 1 & 0 \\
    Y_a(s) & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\
    s/K & 1 \end{bmatrix} \begin{bmatrix} T_d \\
    \omega_{cs} \end{bmatrix}
\]

where \( \omega_{cs} \) is the control surface angular velocity. An overall system transmission matrix, \( T \), can be derived that relates the torques and velocities between the base and control surface, namely,

\[
\begin{bmatrix}
    T_1 \\
    \omega_1 \\
\end{bmatrix} = \begin{bmatrix} A & B \\
    C & D \end{bmatrix} \begin{bmatrix} T_d \\
    \omega_{cs} \end{bmatrix} = T \begin{bmatrix} T_d \\
    \omega_{cs} \end{bmatrix}
\]  

The system model and the various matrices that can be derived enable different transfer functions to be defined and derived analytically in terms of system response requirements.
The next section shows how specifying these types of system-level transfer functions helps define the unknown impedance, $Z_a(s)$. It is then possible to identify the $Z_a(s)$ needed to achieve specified control surface functions. For example, it is possible to find a subsystem to insert at this location that will have passive and/or active components that satisfy a transfer function for $\omega_{cs}/T_d$, which relates control surface velocity to external torque disturbances. This is practically useful since this transfer function is related to the stiffness that the external torque disturbances will ‘feel’ about the control surface rotational axis. The compensation effect can be realized either using a single torque actuator or by separate physical components.

**Actuation System Synthesis**

This section describes how an unknown impedance, $Z_a(s)$, can be derived given an overall system transmission matrix, such as equation 2. The model-basis is needed to derive an analytical form that can be used to specify response requirements. Assume it is required to attenuate the effect of flow-induced torque disturbances, $T_d$, on the control surface angular velocity, $\omega_{cs}$. A model-based relationship between these variables is derived by arranging equation 3 into an immittance ($H$) matrix form (Huelsman, 1963),

$$
\begin{bmatrix}
T_1 \\
\omega_{cs}
\end{bmatrix}
= \frac{1}{D}
\begin{bmatrix}
B & \Delta \\
1 & -C
\end{bmatrix}
\begin{bmatrix}
\omega_1 \\
T_d
\end{bmatrix}
= \begin{bmatrix}
H_{11} & H_{12} \\
H_{21} & H_{22}
\end{bmatrix}
\begin{bmatrix}
\omega_1 \\
T_d
\end{bmatrix}
$$

(4)

where, $\Delta = |T|$. This form includes the transfer function, $H_{22}(s) = \omega_{cs}/T_d$, relating control surface velocity and the disturbance torque. When derived from this model, this transfer function includes an as yet unknown $Z_a(s)$, which can be derived by specifying a desired
function for $H_{22}$. For example, $H_{22}$ might take the form of a band pass or notch filter, in order to attenuate certain flow-induced disturbances arising from an oscillatory or stochastic sea state. To illustrate, consider using a notch filter to attenuate disturbances at a specific frequency, say $\omega_c = 0.5 \text{ rad/s}$. For the notch filter choose $\zeta = 0.1$, and use the gain factor, $K_n$, to adjust dc attenuation level. The results are further simplified here by assuming negligible shaft compliance in the model of Figure 4 so the transmission matrix becomes,

$$
\begin{bmatrix}
A & B \\
C & D
\end{bmatrix} = \begin{bmatrix}
\frac{1}{Z(s)} & b + Js \\
\frac{b + Js}{Z(s)} & b + Js + \frac{1}{Z(s)} + 1
\end{bmatrix}
$$

This leads to an immittance matrix with elements,

$$
\begin{align*}
H_{11} &\Rightarrow \frac{(b+Js)Z_a(s)}{b+Js+Z_a(s)} = U_{11} \\
H_{12} &\Rightarrow \frac{b+Js+Z_a(s)}{b+Js+Z_a(s)} = U_{12} \\
H_{21} &\Rightarrow \frac{b+Js+Z_a(s)}{b+Js} = U_{21} \\
H_{22} &\Rightarrow \frac{b+Js+Z_a(s)}{b+Js+Z_a(s)} = \frac{s^2 + 2\zeta\omega_c + \omega^2_c}{(s + \omega_c)^2}
\end{align*}
$$

By equating $H_{22}$ to a desired notch filter function, the form of $Z_a(s)$ is found as,

$$
Z_a(s) = \frac{b_3s^3 + b_2s^2 + b_1s + b_0}{a_4s^4 + a_3s^3 + a_2s^2 + a_1s + a_0}.
$$

(5)

The coefficients in this relation depend on control surface model and notch filter parameters.

The derived $Z_a(s)$ relates torque, $T_a$, and angular velocity, $\omega_a$, so it is possible to use this function directly in the system model implemented in a commercial block-diagram simulation environment (e.g., Matlab/Simulink, EASY5, etc.). Simulated torque and angular velocity values from this impedance define the actuation characteristics required to achieve the notch filtering behavior. Further, iterative changes in the specified filter characteristics can be used to investigate other types of disturbance canceling designs.

The synthesis procedure continues, however, by decomposing the impedance function, $Z_a(s)$, into simplified terms. Various methods can be used for this purpose, leading to different results, and for this reason synthesis results are not unique. This provides a designer some flexibility in conforming to limitations not included in the analytical synthesis process. The individual terms in an impedance function decomposition can be identified as system components, and the most basic impedance terms are associated with passive components (e.g., compliances, resistances, masses, etc.). Other functional forms that can not be decomposed to basic form can be retained in a more complex impedance form. Of particular interest, however, are negative impedance terms that are associated with active system elements and which this process identifies as a need for an actuation device (e.g., motor, pump, etc.).

To illustrate this process, a partial fraction expansion is used to decompose $Z_a(s)$ from (5), to give,

$$
Z_a(s) = \frac{1}{s} \frac{1}{k_{11}} + \frac{1}{b_{11}} + Z_{\text{active}},
$$

(6)
where $b_{11}$ and $k_{11}$ are positive (rotational) damping and stiffness parameters and $Z_{\text{active}}(s)$ comprises the negative impedance (active) terms from the expansion (for the specific case of a notch filter for $H_{22}$). This result indicates that $Z_a(s)$ can be realized by interconnecting both active and passive impedance components. The decomposed $Z_a(s)$ function can be related to how individual components are actually connected in a system. For example, two impedance functions that add are physically connected in series (e.g., they have the same current or the same velocity). These are commonly known impedance concepts. The decomposed $Z_a(s)$ in Figure 6(a) results in a bond graph form in (b) shown in equivalent network form in (c). This particular decomposition results in a passive combination of capacitive, $C$, and resistive, $R$, components. The other elements arising from the synthesis process are all active elements, since they have negative parameter values, and for this reason are identified as sources of power. In other words, the only way to achieve the specific notch filtering effect is to have an active compensation system. This is a practically useful result. In thinking about realizing the system, a designer might simplify matters by allowing the net effect of the active elements to be consolidated into a single actuator torque, $T_a$, applied between the chassis of the submarine and control surface drive shaft, complemented by the passive compensation. Alternatively, a designer could modify the specified performance and/or use other analytical procedures in order to simplify the system (LeSage, 2010). In the end, the synthesis-aided process provides a preliminary layout and sizing of an actuation subsystem based on desired response and information about the system under retrofit.

In a final system formulation, the results from the synthesis process can be integrated with a feedback control to form a system that will both track and regulate control surface position, as shown in Figure 7. In this way, the total actuator torque is dictated by feedback control of

\[
\begin{align*}
\begin{array}{c}
\begin{tikzpicture}
\node at (0,0) [draw, rounded corners, inner sep=2pt] {
\begin{array}{c}
0 \\
\vdots \\
0
\end{array}
};
\node at (1,0) [draw, rounded corners, inner sep=2pt] {
\begin{array}{c}
0 \\
\vdots \\
0
\end{array}
};
\draw [->] (0.5,0.5) -- (1,0.5);
\node at (1,0.5) {$T_a$};
\node at (1,-0.5) {$\omega_a$};
\node at (1,-1) {$Z_a(s)$};
\node at (2,0) {$\begin{array}{c}
1 \\
\vdots \\
0
\end{array}$};
\node at (2,0.5) {$\omega_a$};
\node at (2,-0.5) {$Z_a(s)$};
\node at (2,-1) {$Z_{\text{active}}(s)$};
\node at (2,-1.5) {$k_{11} : C$};
\node at (2,-2.5) {$R : b_{11}$};
\node at (2,-3.5) {Passive};
\end{tikzpicture}
\end{array}
\end{align*}
\]
\( \delta_{cs} \) as well as by the passive/active compensation derived by synthesis. The net torque on the control surface may then consist of an actuator torque, a passive compensation component, and disturbance torque(s). It is left up to the final design process how the active and passive compensation torques should practically achieved. At this point, simulations should be used to determine how these system configurations compare with a direct controlled ideal torque (no compensation) model as discussed earlier. In this way, alternative forms can be considered for relating actuation system requirements to control surface system requirements.

Figure 8: Simulation results indicating torque required to track a ramp reference command for control surface deflection.
Results from Simulation-Based Evaluation

The process described in the previous two sections is meant to establish a model-basis and alternative systems that can support the retrofit process. Simulation models can be developed to study these results, with the goal of determining the actuator torque-velocity characteristics and associated power and energy required to satisfy specified control surface requirements. For example, results from a simulation for the control surface tracking a ramp input reference command for control surface deflection, $\delta_{ref}$ are summarized in Figure 8. These results are generated with the relatively simple control surface model used in this paper, including disturbance torque models reflecting typical ocean-flow conditions. This actuation subsystem model can be coupled to a full submarine model (Gertler and Hagan, 1967) as described in detail by LeSage (2010). In this way, it would be possible to convert operational requirements for submarine motions into actuation system requirements.

![Figure 9](image-url)  

Figure 9: Comparison of results of simulations for $\delta_{ref} = 0$, contrasting feedback controlled actuation to feedback with active compensation. In this case, a small benefit can be seen in using compensation to reduce long-term energy consumption.

Results are shown in Figure 9 for a case where the feedback controlled torque provides a holding torque to keep the control surface fixed when it is subjected to external disturbances. The graphs also include simulation results for a case where an active compensation is included as described in a previous section. Both cases show that deflection is maintained within about 0.2 degrees of the zero position, and the required torque levels are identical. The only difference is a slight reduction in the required energy for the case that supplements the actuator with active compensation. When the design is changed to have a band-reject
Figure 10: A redesign that targets a band reject rather than notch-filter to reduce the effect of torque disturbances while the system is trying to maintain a fixed angular position. Energy consumption with compensation system is significantly reduced.

rather than notch-filter, the results are improved from the standpoint of controlling the control surface motion as shown in Figure 10. This case also shows that using an actuator combined with a compensation element can significantly reduce power consumption when compared to a system that relies solely on the actuator to regulate control surface position.

Finally, a useful result from this early analysis is the torque versus velocity for a candidate actuation system. Figure 11 compares plots of the actuator torque versus shaft angular velocity for the two different case study designs. It is evident that four quadrant operation is required to maintain a fixed control surface position in both cases. However, a designer can now consider several alternatives, and might prefer the system that has active compensation designed for band-rejection of disturbances since it indicates a lower torque and power demand.

Conclusions and Recommendations

This paper examines modeling and requirements formulation for control surface actuator design and/or retrofit. Since modeling and simulation tools are being used earlier in shipboard system design cycles, the methods discussed here promote a model-based approach for relating system response requirements to actuator subsystem requirements. A synthesis-based method can be applied and configurations and parameter selection can be made based on desired system performance requirements. The methods have been illustrated using a simplified control surface actuation system. It was demonstrated how direct analysis by simulation can be used to determine key requirements necessary for actuator sizing and selection. Both
Figure 11: Torque-speed characteristics for actuator systems designed to reject external disturbance based on a notch-filter (left) and band-reject filter (right).

transient and steady-state simulations, motivated by particular duty cycle characteristics, show how actuator peak torque requirements as well as torque-speed characteristics can be found from this process.

A type of active/passive compensation is derived using the synthesis methods, as a case study on disturbance rejection. The results indicate that there may be some benefit in using these methods to study alternative or augmented actuation schemes. To begin with, the synthesis methods provide a relatively quick way to derive physical compensators for location within an actuation system. Subsequent simulation can be used to show effectiveness or to make decisions on whether to integrate this compensation effect directly into the actuator. Most importantly, the synthesis methods allow a designer to introduce specific system response requirements and to study their influence on the actuation subsystem. In the example studied, it was shown how desired filtering characteristics between control surface motion and external (hydrodynamic) torque disturbances can be designed into an active compensation at the actuation level. In this way, it is shown how multiple requirements might be examined in a similar way through the model-basis illustrated in this paper.

The simplified case studies presented here can be extended and integrated within a full submarine model. This allows demonstrating how ship simulations with required maneuvers can directly generate the actuation system requirements. For example, energy requirements can be derived for specific maneuver types (LeSage, 2010). Further, it was found by comparing two different actuation models that augmenting a feedback controlled torque with a synthesis-derived compensation can lead to reduced energy consumption. Given the need to reduce energy consumption over long missions for many types of ship platforms (especially for unmanned systems), it may be advantageous to examine alternative designs using methods such as those proposed herein.
References


