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STAS Actuator 1.0 – Theory Manual

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ABSTRACT
The STAS Actuator module accounts for the pitch and yaw dynamics, from the commanded angle to the torque applied at the bearing. This is implemented using a second-order filter, together with a spring-damper element and smoothed saturation function.

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Contents

1 Background

The STAS Actuator module provides the link between the commanded blade pitch of the turbine controller, and the torque applied to the slew ring at the blade root. The present implementation includes a standard second-order filter to represent the actuator dynamics. In addition, there are two features of note. First, a spring and damper connect the actuator output with the slew ring. These can be tuned in order to model actuator flexibility and resonance. Second, the saturation of the pitch angle and rate is implemented with a smoothed profile, such that the linearization is locally continuous and numerically precise. This smoothness may be an advantage in Newton's method solution of the nonlinear equations, gradient-based optimization, and other applications that rely on accurate first derivatives.

2 State equations

The pitch and yaw actuation systems are assumed to consist of one or more geared electric motors driving a slew ring. The motor is assumed to provide a commanded pitch rate up to a saturation value. The response of the motor is represented by first-order dynamics with saturation,

$$\frac{d\dot{\beta}_a}{dt} = -\alpha_a \dot{\beta}_a + \alpha_a \hat{\dot{\beta}}_{a*}, \quad \hat{\dot{\beta}}_{a*} = \dot{\beta}_{\max} \, S\left(\frac{\hat{\dot{\beta}}_a}{\dot{\beta}_{\max}}\right), \tag{1}$$

where $S(\,)$ is a unit saturation function, with a splined transition, as shown in Fig. 1. The pitch rate is controlled to drive the pitch error to zero,

$$\hat{\dot{\beta}}_a = K\varepsilon_d, \quad \varepsilon_d = \hat{\beta}_* - \beta_a. \tag{2}$$

The variable $\hat{\beta}_*$ is a saturated pitch command. Define

$$h = \frac{1}{2}(\beta_{\max} - \beta_{\min}) \quad \text{and} \quad g = \beta_{\min} + h. \tag{3}$$

Then,

$$\hat{\beta}_* = h\, S\left(\frac{\hat{\beta} - g}{h}\right) + g. \tag{4}$$

An example is shown in Fig. 2.

The actuator angle is connected to the slew ring by an elastic spring-damper connection, accounting for actuator flexibility. An actuator torque of

$$T = k(\beta_a - \beta) + c(\dot{\beta}_a - \dot{\beta}) \tag{5}$$

is applied to the slew ring.

3 Applying actuator forces to the aeroelastic model

The aeroelastic model (Merz 2018) takes as inputs the nodal forces expressed in body coordinates. In the case of blade pitch, the actuator applies a torque in the negative-x^p direction of the pitch coordinate system, which is the blade's reference coordinate system. This is reacted by a torque in the positive-x^b direction of the blade hub coordinate system. The latter is a part of the driveshaft body, and therefore the torque vector must be transformed to the driveshaft coordinate system. This is accomplished by

$$\mathbf{M}^d = \mathbf{T}^d_{b0} \mathbf{T}^{b0}_b(\boldsymbol{\theta}^{b0}_b)\, \mathbf{M}^b; \qquad \mathbf{M}^b = \begin{bmatrix} T \\ 0 \\ 0 \end{bmatrix}. \tag{6}$$

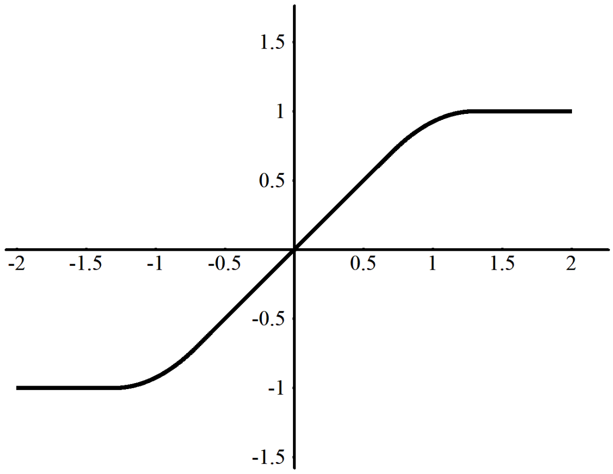

Figure 1: A unit saturation curve with smoothed transition.

The transform $\mathbf{T}^d_{b0}$ is a constant matrix, however the transform $\mathbf{T}^{b0}_b$ varies with the deformation of the driveshaft, as represented by the rotational degrees-of-freedom $\boldsymbol{\theta}^{b0}_b$ for the relevant node.

4 Linearized equations

The actuator state equations are linear except for the saturation functions. These are linearized as

$$\frac{d}{dx}S(f(x)) = \frac{dS}{df}\frac{df}{dx}. \tag{7}$$

So, (1) becomes

$$\frac{d\Delta\dot{\beta}_a}{dt} = -\alpha_a\,\Delta\dot{\beta}_a + \alpha_a\,\frac{dS}{df}\bigg|_{f=\hat{\dot{\beta}}_a/\dot{\beta}_{\max}}\Delta\hat{\dot{\beta}}_a, \tag{8}$$

and similarly, (4) gives

$$\Delta\hat{\beta}_* = \frac{dS}{df}\bigg|_{f=(\hat{\beta}-g)/h}\Delta\hat{\beta}. \tag{9}$$

The applied actuator forces (6) linearize as

$$\Delta\mathbf{M}^d = \mathbf{T}^d_{b0}\mathbf{T}^{b0}_b\,\Delta\mathbf{M}^b + \mathbf{T}^d_{b0}\frac{\partial\mathbf{T}^{b0}_b}{\partial\boldsymbol{\theta}^{b0}_b}\mathbf{M}^b_0\,\Delta\boldsymbol{\theta}^{b0}_b. \tag{10}$$

References

[1] Merz KO (2018). *STAS Aeroelastic 1.0 – Theory Manual.* Report 2018:00834, SINTEF Energy Research.

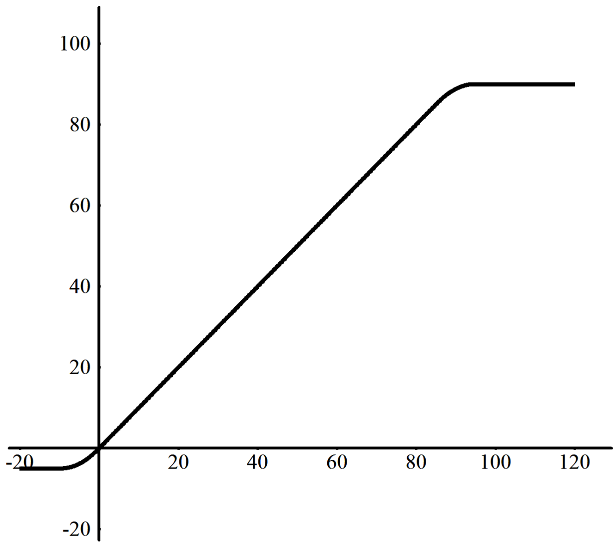

Figure 2: An example of pitch angle saturation at -5° *and* 90°.

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