

## Quaternion differentiation

Quaternion differentiation's formula connects time derivative of component of quaternion  $q(t)$  with component of vector of angular velocity  $W(t)$ . Quaternion  $q(t)=(q_0(t), q_1(t), q_2(t), q_3(t))$  determines attitude of rigid body moving with one fixed point, vector of angular velocity  $W(t)=(W_x(t), W_y(t), W_z(t))$  determines angular velocity of this body at point of time  $t$ . point of time. Norm of quaternion  $q(t)$  is unit, i.e.

$$q_0^2(t) + q_1^2(t) + q_2^2(t) + q_3^2(t) = 1$$

(1)

Vector  $W(t)$  can be represented as quaternion with zero scalar part, i.e

$$W(t) = (0, W_x(t), W_y(t), W_z(t))$$

(2)

Quaternion differentiation's formula can be represented as

$$\frac{dq(t)}{dt} = \frac{1}{2} W(t)q(t)$$

(3)

Using quaternion multiplication rule

$$\frac{dq_0(t)}{dt} = -\frac{1}{2} (W_x(t)q_1(t) + W_y(t)q_2(t) + W_z(t)q_3(t))$$

$$\frac{dq_1(t)}{dt} = \frac{1}{2} (W_x(t)q_0(t) + W_y(t)q_3(t) - W_z(t)q_2(t))$$

$$\frac{dq_2(t)}{dt} = \frac{1}{2} (W_y(t)q_0(t) + W_z(t)q_1(t) - W_x(t)q_3(t))$$

$$\frac{dq_3(t)}{dt} = \frac{1}{2} (W_z(t)q_0(t) + W_x(t)q_2(t) - W_y(t)q_1(t))$$

(4)

Below formula (3) brief and vigorous derivation follows.

Let  $R_0$  is any given vector (quaternion with zero scalar part) fixed in rigid body at initial moment of time  $t_0$ ,  $R_t$  is the same vector (quaternion) at moment of time  $t$ . Then, obviously

$$R_t = q(t)R_0q^{-1}(t)$$

(5)

If we differentiate (5) then

$$\frac{dR_t}{dt} = \frac{dq(t)}{dt}R_0q^{-1}(t) + q(t)R_0\frac{dq^{-1}(t)}{dt}$$

(6)

From (5) and (6) we have

$$\frac{dR_t}{dt} = \frac{dq(t)}{dt} q^{-1}(t) R_t + R_t q(t) \frac{dq^{-1}(t)}{dt}$$

(7)

Because norm of quaternion  $q(t)$  is unit, i.e.

$$q(t)q^{-1}(t) = 1$$

(8)

we have

$$\frac{dq(t)}{dt} q^{-1}(t) + q(t) \frac{dq^{-1}(t)}{dt} = 0$$

(9)

It follows from (7) and (9) that

$$\frac{dR_t}{dt} = \frac{dq(t)}{dt} q^{-1}(t) R_t - R_t \frac{dq(t)}{dt} q^{-1}(t)$$

(10)

Let

$$p(t) = \frac{dq(t)}{dt} q^{-1}(t)$$

(11)

Obviously

$$q^{-1}(t) = S(q^{-1}(t)) + V(q^{-1}(t)) = q_0(t) - (q_1(t), q_2(t), q_3(t))$$

(12)

where  $S()$  = scalar part,  $V()$  = vector part of quaternion

Scalar part  $S(p(t))$  of quaternion  $p(t)$  equals

$$S(p(t)) = \frac{dq_0(t)}{dt} q_0 + \frac{dq_1(t)}{dt} q_1 + \frac{dq_2(t)}{dt} q_2 + \frac{dq_3(t)}{dt} q_3 = 0$$

because norm of quaternion  $q(t)$  is unit.

It follows that  $p(t)$  is vector. Because  $R_t$  is also vector

$$p(t)R_t - R_t p(t) = 2[p(t)R_t]$$

(13)

where  $[ab]$  = cross-product of vector  $a$  and vector  $b$ .

On the other hand, variable  $\frac{dR_t}{dt}$  is velocity of point of rigid body with one fixed point. Hence

$$\frac{dR_t}{dt} = [W(t)R_t]$$

(14).

Because  $R_t$  is arbitrary vector, it follows from (10), (11), (13) and (14)

$$W(t) = 2p(t) = 2\frac{dq(t)}{dt}q^{-1}(t)$$

(15)

It follows from (15) finally that

$$\frac{dq(t)}{dt} = \frac{1}{2}W(t)q(t)$$

(3)

It is necessary to draw attention: in formula (3) angular velocity vector  $W(t)=(W_x(t), W_y(t), W_z(t))$  is represented by projections on axes of unmoving system of coordinates. If we apply the projections on axes of moving system of coordinates for the same angular velocity vector then obviously:

$$(0, W_x(t), W_y(t), W_z(t)) = q(t)(0, W_x(t), W_y(t), W_z(t))q^{-1}(t)$$

(16)

Where  $W_x(t), W_y(t), W_z(t)$  are projections of angular velocity vector on axes of moving system of coordinates.

It follows from (3) and (16) that

$$\frac{dq(t)}{dt} = \frac{1}{2}q(t)\overline{W}(t)$$

$$\overline{W}(t) = (W_x(t), W_y(t), W_z(t))$$

(17)

Finally, consider example of formulas (3) and (17) using for so-called conic moving. In this case quaternion  $q(t)$  equals:

$$q(t) = \left(\cos\left(\frac{\beta}{2}\right), \sin\left(\frac{\beta}{2}\right)(\cos(\omega t), \sin(\omega t), 0)\right)$$

$$q^{-1}(t) = \left(\cos\left(\frac{\beta}{2}\right), -\sin\left(\frac{\beta}{2}\right)(\cos(\omega t), \sin(\omega t), 0)\right)$$

$$\frac{dq(t)}{dt} = \left(0, \omega \sin\left(\frac{\beta}{2}\right)(-\sin(\omega t), \cos(\omega t), 0)\right)$$

(18)

Accordingly (3) and (17) projections of angular velocity vector on axes of unmoving and moving systems of coordinates equals:

$$(W_x(t), W_y(t), W_z(t)) = 2 \frac{dq(t)}{dt} q^{-1}(t) = (-\omega \sin(\beta) \sin(\omega t), \omega \sin(\beta) \cos(\omega t), \omega(1 - \cos(\beta)))$$

$$(W_x(t), W_y(t), W_z(t)) = 2 q^{-1}(t) \frac{dq(t)}{dt} = (-\omega \sin(\beta) \sin(\omega t), \omega \sin(\beta) \cos(\omega t), \omega(\cos(\beta) - 1))$$