Appendix A

Note on the Damping Term

A.1 Abstract

A rigorous equation of polar motion is presented on the assumption of familiar "Newtonian" damping. As long as the Q–value is independent of frequency and as high as O(100) or less as estimated in previous works [e.g., *Wilson and Vicente*, 1990; *Furuya and Chao*, 1996], the difference between the conventional and present equation of motion would be insignificant.

Key words: polar motion, wobble, equation of motion, damping.

A.2 Motivation

The conventionally employed equation of the Earth's wobble is the following;

$$\frac{i}{\tilde{\sigma}_{CW}}\frac{d\tilde{\mathbf{m}}}{dt} + \tilde{\mathbf{m}} = \tilde{\chi}, \tag{A.1}$$

where the $\tilde{\mathbf{m}}$ represents wobble, and is defined as $m_1 + im_2$ when the variable angular velocity vector is set to be $\Omega(m_1, m_2, 1 + m_3)$; the subscript 1 and 2 denote the Greenwich meridian and 90 deg. east longitude, respectively. The RHS of eq. (A.1), $\tilde{\chi}$, represents the excitation, which is defined as $\chi_1 + i\chi_2$ [e.g., *Munk and MacDonald*, 1960; *Lambeck*, 1980; *Eubanks*, 1993]. Note that the eq. (A.1) allows for a 2–dimensional damped linear oscillator with its resonant frequency, $\tilde{\sigma}_{CW}$, which is defined in terms of Chandler period, T, and Q–value:

$$\tilde{\sigma}_{CW} \equiv \frac{2\pi}{T}(1 + i\frac{1}{2Q}). \qquad (A.2)$$

In view of the eqs. (A.1) and (A.2), the i in $m_1 + im_2$ as well as in $\chi_1 + i\chi_2$ is obviously for a numerical convenience in expressing a 2–D quantity. On the other hand, the i in $\tilde{\sigma}_{CW}$ has been connected to the imaginary part of the complex Love number [e.g., *Lambeck*, 1980]. It is true that the complex Love number itself is allowable for some linear rheologies [*Lambeck*, 1980], but it is defined not in time domain but in frequency domain; it would not be legitimate to meet the two different i in one equation. Rather, despite that the explicit form of damping term had not yet been confirmed, it appears that the real eigenfrequency was simply replaced with the complex eigenfrequency in *ad hoc* manner in the previous works.

A.3 Formulation and Result

In the conventional derivation of eq. (A.1), the feed back term with complex coefficient is added to the Euler equation for rigid spheroid, which allows for both the elastic yielding of the mantle by the real part and the phase lag associated with dissipation by the imaginary part [e.g., *Lambeck*, 1980]; at this time, the two i are errorneously mixed together. The Q–value has often been related with the imaginary part of Love number, and this has been the basis for arguments on mantle anelasticity. However, if we regard that the i in eq. (A.1) is just for numerical convenience, what kind of term is invoked as the dissipative torque? Decomposing the eq. (A.1) into real and imaginary part, one arrives at the damping term as the second term in the LHS of eq. (A.3) below;

$$\text{Real} \quad \frac{1}{\sigma^*}(-\frac{dm_2}{dt} + \frac{1}{2Q}\frac{dm_1}{dt}) + m_1 \;=\; 0, \qquad (A.3a)$$

$$\text{Imag} \quad \frac{1}{\sigma^*}(\frac{dm_1}{dt} + \frac{1}{2Q}\frac{dm_2}{dt}) + m_2 \;=\; 0, \qquad (A.3b)$$

where σ^* is defined as $\sigma_{CW}(1 + 1/4Q^2)$. It is certain that this equation allows the free damped oscillation of eq. (A.4):

$$m_1 \;=\; \exp(-t/2QT)\cos(2\pi t/T), \qquad (A.4a)$$

$$m_2 \;=\; \exp(-t/2QT)\sin(2\pi t/T). \qquad (A.4b)$$

However, we should note that the damping term is *not* a familiar “Newtonian” damping; *Munk and MacDonald* [1960] states that the torque above corresponds to the frictional torque acting in a direction opposite to the motion of the shell shifting in response to the wobble. It turns out that the Q–value in eq. (A.1) defined as (A.2) originates in the above frictional torque. This type of torque has been considered to work as the dissipation in the core [*Munk and MacDonald*, 1960; *Lambeck*, 1980].

As shown in *Munk and MacDonald* [1960], there is another choice for the damping term. We add the well-known ‘Newtonian’ damping into the original equation for rigid body. How will be the conventional eq. (A.1) altered? The ‘Newtonian’ damping is the third term of LHS of eq. (A.5) below,

$$A_m\frac{dm_1}{dt} + \Omega(C - A)(1 - \frac{k_2^W}{k_0})m_2 + \alpha m_1 \;=\; L_2, \qquad (A.5a)$$

$$A_m\frac{dm_2}{dt} - \Omega(C - A)(1 - \frac{k_2^W}{k_0})m_1 + \alpha m_2 \;=\; -L_1, \qquad (A.5b)$$

where C and A are the principal moments of inertia around the polar and equatorial axis, respectively, and $L_j(j = 1, 2)$ is the torque around the axis denoted as j; A_m represents the equatorial principal moment of inertia for only the mantle. Unlike the conventional derivation, the wobble Love number, k_2^W, is not a complex but a real value. Combining eqs. (A.5a) and (A.5b) in terms of i and based on the eq. (A.2), we arrive at the following equation:

$$\frac{i}{\sigma_{CW}}\frac{d\tilde{\mathrm{m}}}{dt} + \tilde{\mathrm{m}}[1 + i\frac{1}{2Q^*}] \;=\; \tilde{\chi}^*, \qquad (A.6a)$$

$$\text{with} \quad \sigma_{CW} = \frac{(C-A)\Omega}{A_m}\left(1-\frac{k_2^W}{k_0}\right), \tag{A.6b}$$

$$Q^{*-1} = \frac{2\alpha}{\sigma_{CW}}. \tag{A.6c}$$

Here, we attached the asterisk in both the excitation and Q in order to distinguish them in eq. (A.3). The fundamental difference from the above derivation is that the i in eq. (A.6a) is used just for the purpose of numerical convenience. The real and imaginary part of eq. (A.6a) are the following;

$$\frac{1}{\sigma_{CW}}\frac{dm_1}{dt} + m_2 + \frac{m_1}{2Q} = \chi_2^*, \tag{A.7a}$$

$$\frac{1}{\sigma_{CW}}\frac{dm_2}{dt} - m_1 + \frac{m_2}{2Q} = -\chi_1^*, \tag{A.7b}$$

which obviously yield the eigen solution of eq. (A.4).

A.4 Discussion

We re-examined the polar motion equation from the standpoint that two distinct i should not be used in one equation of motion. As long as we assume the simple linear damped oscillation of eqs. (A.4), and allow for only the i used just for numerical convenience, there are two kinds of strictly permissible damping terms, i.e., the second terms in eqs. (A.3) and the third terms in eqs. (A.7). Thus, both eqs. (A.3) and (A.3) can be the polar motion equation, while eqs. (A.3) have been traditionally employed. When we resort to the 'Newtonian' damping as in eqs. (A.7), the eq. (A.6a) have to be employed in place of eq. (A.1).

In the previous literature on the excitation of Earth's wobble, the deconvolution of observed wobble into its excitation has been carried out in terms of eq. (A.1) by assuming the Chandler period and Q-value [e.g., *Wilson and Haubrich*, 1976; *Wahr*, 1983; *Wilson*, 1985]. If one employes eq. (A.6a), what difference would be seen in the inferred excitation? Comparing the $\tilde{\chi}$ in eq. (A.1) with the $\tilde{\chi}^*$ in eq. (A.6a), the following relation can

be retained if both Q and Q^* are numerically the same with each other;

$$\tilde{\chi}^* = \tilde{\chi}\left(1 + i\frac{1}{2Q}\right). \tag{A.8}$$

If the Q-value is independent of frequency and as high as O(100) or less as estimated in previous works [e.g., *Wilson and Vicente*, 1990; *Furuya and Chao*, 1996], the difference would be insignificant in spite of the considerable difference in the appearance between eqs. (A.3) and (A.7).

Appendix B

Note on the Bias for Chandler Frequency Estimate

B.1 Abstract

Based on the recent understanding that the atmospheric angular momentum (AAM) fluctuation is partially responsible for the excitation of Chandler wobble, a few groups have tried to estimate the Chandler frequecy by minimizing the difference between AAM and inferred excitation [*Furuya and Chao*, 1996]. The purpose of this note[1] is to show that the Chandler frequency estimate tends to be biased toward higher value than the true frequency.

B.2 Formulation and Result

Polar motion is thought to follow the basic equation of polar motion, eq. (B.1):

$$\frac{i}{\tilde{\sigma}_{CW}}\frac{d\tilde{\mathrm{m}}}{dt}+\tilde{\mathrm{m}}=\tilde{\chi}, \tag{B.1}$$

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[1] This appendix has been arranged for *Furuya and Chao* [1996].

where the $\tilde{\mathbf{m}}$ represents wobble, and is defined as $m_1 + im_2$ when the variable angular velocity vector is set to be $\Omega(m_1, m_2, 1 + m_3)$; the subscript 1 and 2 denote the Greenwich meridian and 90 deg. east longitude, respectively. The $\tilde{\chi}$ represents its excitation, which is defined as $\chi_1 + i\chi_2$ [e.g., *Munk and MacDonald*, 1960; *Lambeck*, 1980; *Eubanks*, 1993]. Note that the eq. (B.1) allows for a 2–dimensional damped linear oscillator with its resonant frequency, $\tilde{\sigma}_{CW}$, which is defined in terms of Chandler period, T, and Q–value:

$$\tilde{\sigma}_{CW} \equiv \frac{2\pi}{T}(1 + i\frac{1}{2Q}). \tag{B.2}$$

We can infer the excitaion by prescribing the complex Chandler frequency as $\tilde{\sigma}_a$; the Wilson's filter is used here [*Wilson*, 1985].

When the prescribed $\tilde{\sigma}_a$ differs from the true $\tilde{\sigma}_{CW}$ (which would be probably always the case!), how different is the inferred excitation $\tilde{\chi}_a$ from the true $\tilde{\chi}$? After a simple algebra, the $\tilde{\chi}_a$ can be written as follows:

$$\tilde{\chi}_a(t) = \frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a}[\tilde{\chi}(t) - \tilde{\mathbf{m}}(t)] + \tilde{\mathbf{m}}(t), \tag{B.3}$$

which obviously illustrates that we cannot know the true $\tilde{\chi}$ until the $\tilde{\sigma}_a$ coinsides with the $\tilde{\sigma}_{CW}$.

Suppose that the $\tilde{\chi}$ consists of both $\tilde{\chi}_{AAM}$ and other unknown $\tilde{\chi}_N$,

$$\tilde{\chi} = \tilde{\chi}_{AAM} + \tilde{\chi}_N. \tag{B.4}$$

In order to estimate the optimum Chandler frequency, we minimize the residual between $\tilde{\chi}_a$ and $\tilde{\chi}_{AAM}$. With the use of eq. (B.3), we see that the difference is the following;

$$\begin{aligned} \tilde{\chi}_a - \tilde{\chi}_{AAM} &= \frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a}(\tilde{\chi}_{AAM} + \tilde{\chi}_N - \tilde{\mathbf{m}}) + \tilde{\mathbf{m}} - \tilde{\chi}_{AAM} \\ &= (\tilde{\chi}_{AAM} - \tilde{\mathbf{m}} + \tilde{\chi}_N)(\frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a}) - (\tilde{\chi}_{AAM} - \tilde{\mathbf{m}}), \end{aligned} \tag{B.5}$$

which can be viewed in both time and frequency domain.

At some specfied frequency σ_i, the residual power $r(\sigma_i)$ is,

$$\begin{aligned} r(\sigma_i) &= [\tilde{\chi}_{AAM} - \tilde{\mathbf{m}} + \tilde{\chi}_N]^2(\frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a})^2 \\ &\quad -2[\tilde{\chi}_{AAM} - \tilde{\mathbf{m}}][\tilde{\chi}_{AAM} - \tilde{\mathbf{m}} + \tilde{\chi}_N](\frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a}) \\ &\quad +[\tilde{\chi}_{AAM} - \tilde{\mathbf{m}}]^2. \end{aligned} \tag{B.6}$$

Now, let us consider a statistical properties of $r(\sigma_i)$. If the following equality is assumed to hold, i.e.,

$$E[(\tilde{\chi}_{AAM} - \tilde{\mathbf{m}}) \cdot \tilde{\chi}_N] = 0, \tag{B.7}$$

the eq. (B.6) will lead into the following,

$$\begin{aligned} E[r(\sigma_i)] &= [\tilde{\chi}_{AAM} - \tilde{\mathbf{m}} + \tilde{\chi}_N]^2(\frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a})^2 \\ &\quad -2[\tilde{\chi}_{AAM} - \tilde{\mathbf{m}}](\frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a}) \\ &\quad +[\tilde{\chi}_{AAM} - \tilde{\mathbf{m}}]^2 && \text{(B.8)} \\ &= (R_i + N_i)(\frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a})^2 - 2R_i(\frac{\tilde{\sigma}_{CW}}{\tilde{\sigma}_a}) + R_i, && \text{(B.9)} \end{aligned}$$

where R_i and N_i are defined as follows, respectively;

$$\begin{aligned} R_i &= [\tilde{\chi}_{AAM} - \tilde{\mathbf{m}}]^2, && \text{(B.10)} \\ N_i &= \tilde{\chi}_N^2. && \text{(B.11)} \end{aligned}$$

Here, the assumption of eq. (B.7) will be legitimate as long as the non-AAM excitation $\tilde{\chi}_N$ has no coherence with the AAM. Moreover, the dot-product, $\tilde{\mathbf{m}} \cdot \tilde{\chi}_N$, corresponding to their convolution in time domain will be small in its expectation value.

The minimum residual power of is achieved when the prescribed frequency is

$$\tilde{\sigma}_a = \frac{R_i + N_i}{R_i} \cdot \tilde{\sigma}_{CW}. \tag{B.12}$$

B.3 Conclusion

If one employs wide frequency band and minimizes the residual power, the minimum is achieved when the prescribed frequency is

$$E[\tilde{\sigma}_a] = \frac{\sum R_i + \sum N_i}{\sum R_i} \cdot \tilde{\sigma}_{CW}, \tag{B.13}$$

where the summation is performed over the frequencies taken into account. Thus, we are led to conclude that the Chandler frequency tends to be estimated higher than the true frequency.

Afterword

This thesis is concerned with the classical geophysical problem, to examine the excitation source(s) of the Earth's wobble. Some people will consider the term, classic, as "old-fashioned", but I am using the term as *having a high quality that is recognized and unquestioned*[2]. My impression is that the earnest work has just begun over the past decade, partly because the space-geodetic technique can provide a good quality data set and parly because the global atmospheric analysis data have proven to be useful for studying the variable Earth rotation. Indeed, all the results shown in later Chapters are my original results which, to my knowledge, have never appeared in previous literature.

In the near future, the time span of space-geodetic observation will be extended. Moreover, the global data assimilation technique will involve not only the atmosphere but also the ocean and hydrosphere on the land. Hopefully, this book would serve as one step for the future research in this area.

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[2] Oxford Advanced Lerner's Dictionary of Current English. 4th edition.

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