Stratospheric Balloon-Borne "Adapted Gill-Type" Propeller Anemometer

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ABSTRACT

In order to observe stratospheric gravity waves and turbulence, a Gill-type anemometer was improved by using sapphire pivot bearings and photocoupler tachometers. The anemometer has a threshold velocity of less than 1 m s^{-1} in the middle stratosphere, and the performance is very stable for mechanical shocks and temperature variations. The first observational flight of the anemometer was successfully carried out in September 1982. The most interesting result of this observation is that there often exist gust-like wind fluctuations of $1\text{--}3 \text{ m s}^{-1}$ in the stratosphere.

1. Introduction

We planned stratospheric balloon observations during the period of MAP (Middle Atmosphere Program, 1982–85) in order to reveal the origin and nature of stratospheric turbulence, especially in relation to gravity waves (see Yamanaka and Tanaka, 1984a). Although several observational studies using balloons and radars have been carried out (e.g., Barat, 1975, 1982; Cadet, 1975, 1977; Cadet *et al.*, 1977; Woodman, 1981; Sato and Woodman, 1982), the relation between turbulence and gravity waves has not yet been clarified. Measurements of stratospheric turbulence and gravity waves are important for a quantitative understanding of friction for the general circulation in the stratosphere (Tanaka and Yamanaka, 1985) and also in the mesosphere since gravity waves may propagate upward through the stratosphere (*viz.*, Lindzen, 1981; Matsuno, 1982).

For the aforementioned purpose, we must observe wind fluctuations caused by mesoscale waves and microscale turbulence at the same time; the time scales range from a few seconds to a day. In particular, as Yamanaka and Tanaka (1984b) pointed out theoretically, the breaking of long-period gravity waves may be somewhat different from that of simple gravity waves studied by many investigators (e.g., Tanaka, 1983). Also, the spatial microstructures should be observed to reveal the mechanism and life cycles of turbulence; a vertical resolution smaller than some tens of meters is necessary. The only way to accomplish our purpose

is to use balloons on which are mounted one or more anemometers sensitive enough to detect the wind velocity relative to the balloon.

We present here an "adapted Gill-type" anemometer† used in our first observation carried out in September 1982. The plan for the balloon observation is introduced in section 2. A description of how the anemometer was adapted is provided in section 3. Results of the first flight test are discussed in section 4. With regard to geophysical interpretation of the results, a quick-look report (Yamanaka and Tanaka, 1984c) has been published.

2. Balloon system

After referring to previous studies (e.g., Cadet, 1977; Cadet *et al.*, 1977; Barat, 1982), we planned to observe stratospheric wind fluctuation by three techniques simultaneously (see Table 1): i) balloon tracking, ii) propeller anemometers and iii) ionic anemometers. The sensor (iii) was prepared for the second flight in 1983 and is not discussed in this paper. A radio-controlled winch system and a sensitive balloon ascent meter are also borne on the balloon gondola to obtain the microstructure of wind fluctuations with high resolution and accuracy (see section 4). The winch system was

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† Note added in proof. Gill and MacCready, each in unpublished works, used a larger propeller and a lower-friction bearing, respectively, and their anemometers seem to be more sensitive than ours. Although such sensitivity improvements are reasonable (see section 3), the former implies a lower spatial resolution. We consider ours an optimum adaptation with respect to sensitivity, resolution and strength for stratospheric balloon-borne use.

TABLE 1. Observational methods for stratospheric phenomena.

Horizontal scale (km)	Range						
	$\sim 10^{-2}$	$\sim 10^{-1}$	$\sim 10^0$	$\sim 10^1$	$\sim 10^2$	$\sim 10^3$	$\sim 10^4$
Time scale	~ 1 s		~ 1 min		~ 1 hour	~ 1 day	~ 1 week
Intrinsic frequency*			N			f	βL
Dynamical phenomena*					Internal gravity wave		Rossby wave
					(IIGW)		
Wind amplitude (m s^{-1})	10^{-2}	10^{-1}	10^0			10^1	
	(Turbulence)						
	← Ionic anemometer						
Measurement technique		← Propeller anemometer					
			← Balloon tracking				

* N : Väisälä-Brunt frequency ($\approx 2 \times 10^{-2} \text{ s}^{-1}$). f : Coriolis factor ($\approx 1 \times 10^{-4} \text{ s}^{-1}$). β : Rossby parameter ($\approx 1 \times 10^{-11} \text{ m}^{-1} \text{ s}^{-1}$). L : Horizontal wavelength. IIGW: Internal inertia-gravity wave.

developed by Matsuzaka *et al.* (1985); other engineering performance and accessories of our observation balloon are conventional in scientific ballooning in Japan (see, e.g., Nishimura and Hirose, 1981). See Fig. 1 for the balloon system used for the observations.

As shown in Table 1, the propeller anemometer should cover a dynamic range of $1\text{--}10 \text{ m s}^{-1}$. Note that, although many types of anemometers are used for measuring turbulence in the planetary boundary layer (see, e.g., Wyngaard, 1981), almost all of them are considered to be unsuitable for stratospheric balloon observations for the following three reasons: 1) the low density ($10\text{--}0.1\%$ of the surface air), 2) the low temperature ($\leq -50^\circ\text{C}$) and 3) mechanical shocks in launching and in flight (approximately twice that of gravity). However, the propeller-type anemometer has simple measuring principles that can easily be improved for our purpose (see section 3). It is also stable for long duration observations and may be used as a standard gauge if a more sensitive anemometer like the ionic type is mounted with it.

3. Adaptation of Gill anemometer

a. Principle and problems

The Gill-type propeller anemometer, originally developed by Holmes *et al.* (1964), is one of the standard sensors for measuring atmospheric turbulence near the ground. The measuring principle of propeller anemometers has been well studied (see, e.g., MacCready and Jex, 1964), and points relating to this principle are summarized in appendix A. The nearly linear output of a Gill-type anemometer for sufficiently strong wind velocities does not depend on the surrounding air pres-

sure. Therefore the anemometer can be used for measurements of various altitudes without recalibration.

However, the threshold velocity (u_0) and the time constant (τ) of the anemometer depend on the pressure (p) as follows if the air temperature is nearly constant:

$$u_0 \propto K^{1/2} \cdot p^{-1/2}, \quad (1)$$

$$\tau \propto \bar{u}^{-1} \cdot p^{-1}, \quad (2)$$

FIG. 1. Balloon system used in the September 1982 observation.

where K is the frictional torque of the propeller anemometer, and $\bar{u}$ denotes a wind speed to be measured. Equations (1) and (2) imply that the sensitivity and response of the anemometer become inferior as the pressure decreases. It should be noted that u_0 and τ are functions not of p but of the air density in more generalized forms (see appendix A). Thus the sensitivity and response may be slightly improved in the stratospheric low temperatures; u_0 and τ in -50°C become respectively 85 and 73% of those in 20°C . However, we shall omit these corrections to simplify the description.

A series of wind-tunnel experiments were carried out for a standard Gill-type anemometer, Model AGP-230, sold by Makino Applied Instruments, Inc. The calibrations of wind velocity were done by measurements of dynamic pressures using a semiconductor manometer. The temperature inside the wind-tunnel ranges between 17.2 – 23.5°C . We obtained $u_0 = 2.7 \text{ m s}^{-1}$ and the length constant $\lambda \equiv \tau \cdot \bar{u} = 42 \text{ m}$ at 20 Torr (26.7 hPa) pressure for the AGP-230 sensor. These results imply that such ready-made sensors are useless for stratospheric balloon observations.

From this principle, we find that K should be reduced in order to compensate for the pressure decrease.¹ It is caused by the friction of bearings supporting the rotating shaft and by the brush friction and electromagnetic induction of the rotation-detection generator. To decrease these frictions we utilized jewel bearings, a pivotal propeller shaft and photocoupler detectors as shown below.

b. Jewel bearings and pivots

In balloon-borne anemometer use we must contend with launching shocks about twice the force of gravity and temperature variations from $+30$ to -50°C . Thus oil lubrication, magnetic bearings and air bearings are not appropriate. We used pairs of sapphire cup bearings and SK-steel pivots (3A-471, Ogura Jewel Industry Co.). The cups and the pivots were set on the support and on the ends of the propeller shaft, respectively (see Fig. 2). The cup bearing can be shifted slightly by the use of a small spring between it and the support, so that the contact-point shifts within 1 mm. The friction between the pivot and bearing was designed to be uniform within such a dynamic range of the contact point.² The support is made in a rectangle of brass rods (10 mm diam.), which is sufficiently strong for the shocks

FIG. 2. Construction of the adapted Gill-type anemometer (units: mm): (a) Gill-type propeller, (b) sapphire cup bearing, (c) SK-steel pivot, (d) light-emitting diode, (e) phototransistor.

expected, and it does not seriously modify the effective area of the standard Gill-type propeller (23 cm diam.).

The torques of the AGP-230 anemometer and the adapted Gill-type anemometer for various ambient temperatures are shown in Fig. 3. The torques were obtained from measurements of damping oscillations of a pendulum attached to the propeller shaft which was placed between a laser beam source and photo-sensors. We find that the torque of the adapted anemometer is about $1/7$ of that of AGP-230 at normal temperatures, which implies that the threshold velocity is improved to $2.7 \text{ m s}^{-1} \times \sqrt{1/7} \sim 1 \text{ m s}^{-1}$ at 20 Torr. It is also found, as shown in Fig. 3, that the adapted anemometer is very stable over a large range of temperatures. The oil lubrication used (KF-50, Shin-Etsu Chemical Co.) is useless for friction reduction, possibly because the effective contact area of the bearing becomes enlarged.

c. Photocoupler rotation counter

For measurement of the propeller rotation without any friction, we used two parallel sets of light-emitting diodes (TLN101C) and phototransistors (TPS601A) attached to the support (see Fig. 2). As the propeller rotates across infrared rays emitted from the diodes, the transistors put out two series of voltage pulses with a phase difference. The pulses are counted including the rotating directions by using a 4-bit up/down counter (CD4516) and a phase-difference detector (CD4013).

¹ There is another way to improve the sensitivity, that is, to use a propeller larger than the standard one of 23 cm diameter (see appendix A). However, this is inadequate for measuring stratospheric turbulence, since the minimum eddy diameter in the stratosphere is considered to be 10 cm or smaller. Refer to the footnote in section 1.

² Thus, the bearing of a balloon-borne anemometer has an optimum friction. See the footnote of section 1.

FIG. 3. Frictional torques of the AGP-230 and adapted Gill type anemometers. "Oiled" means that the pivot bearings are lubricated by silicon oil.

The output of the adapted Gill-type anemometer is a count of those pulses, which corresponds to a time-integrated wind velocity. This is appropriate for detection of very weak winds around the threshold velocity. The output count is directly transmitted to the ground, where the wind velocity is calculated from the count data differentiated every six seconds using a micro-computer.

d. Calibrations

Considering the excellent angular characteristics of the Gill-type propeller (see Holmes *et al.*, 1964; Gill, 1975), we used a standard 4-blade 23 cm diam propeller, without modification, made by R. M. Young Co. Therefore, from the principle mentioned in subsection 3a and appendix A, the response of the adapted anemometer is essentially the same as that of the usual Gill-type anemometer. Since the length constant is 42 m at 20 Torr, the time constant becomes 42 and 8 s for middle-stratospheric wind velocities of 1 and 5 m s⁻¹, respectively. Stall regions around wind angles of $\pm 90^\circ$ exist also in the adapted anemometer.

Figure 4a, b shows the calibration curves of the AGP-

230 anemometer and the adapted Gill-type anemometer, respectively. The calibration experiments were carried out by the same method as that described in subsection 3a. The curves shown in Fig. 4a, b are hyperbolic curves (cf. appendix A) which were obtained by using the method of least squares. The asymptotes of these curves agree well with the linear characteristics in the normal pressures. We find from Fig. 4b that the threshold velocity of the adapted anemometer is about 0.9 m s⁻¹ at 20 Torr pressure, which is consistent with the value expected from the torque measurements discussed in subsection 3b. In Fig. 5, the threshold velocity and time constant of the adapted anemometer are shown for various altitudes based on Eqs. (1) and (2). Anemometer specifications are summarized in Table 2.

The accuracy of the adapted anemometer is about ± 0.1 m s⁻¹ except for the hysteresis region near the threshold velocity. The data deviations shown in Fig. 4 may be explained by air temperature variations during the calibration experiments. As noted in subsection 3a, the threshold velocity and distance constant at 20 Torr improved to 0.75 m s⁻¹ and 31 m, respectively, when the anemometer is to be used in stratospheric low temperature ($\leq -50^\circ\text{C}$).

FIG. 4. Calibration curves at 20 Torr (26.7 hPa) pressure in normal temperatures: (a) AGP-230, (b) adapted Gill-type anemometer. Dots are experimental results, and curves are the optimum hyperbolic curves calculated from the experimental data by using the method of least squares (see text).

4. The first observational flight

a. Samples of anemometric records

We carried out the first balloon observation of stratospheric turbulence and gravity waves using adapted Gill-type anemometers on 20–21 September 1982 (see Yamanaka and Tanaka, 1984a,c). Two sets of anemometric instruments were mounted on two gondolas as shown in Fig. 1. In order to determine the direction of relative winds, we arranged two adapted Gill-type sensors perpendicularly on a horizontal plane of each gondola. The attitude of each gondola was continuously monitored by an accurate geomagnetic sensor. Note that use of a vane for such monitoring is inappropriate because its inertia is too great for it to respond to microscale wind fluctuations. The balloon motion was observed with high accuracy using a radar transponder (locating accuracy < 100 m) and a barometric ascent meter (accuracy < 1 Pa), and it was controlled by operating an exhaust valve and ballasting (see Nishimura and Hirosawa, 1981).

Surveys along the vertical of relative horizontal winds with high resolution were carried out by reeling the lower gondola up and down using a winch mounted on the upper gondola (Matsuzaka *et al.*, 1985). During each survey, variations of the balloon-flight level were within 50 m or less, according to the ascent meter data. The mean flow of the flight level was weak westerly (~ 4 m s $^{-1}$). The adapted Gill anemometers on the lower gondola detected relative wind speed variations as shown in Fig. 6, for example, where the data were

obtained from vector sums of the two component outputs every six seconds. The following four types of wind fluctuations can be detected:

FIG. 5. Sensitivity and response of the adapted Gill-type anemometer for various altitudes. The solid curve is the threshold velocity (labeled in the lower abscissa). The dashed curves denote the time constants (labeled in the upper abscissa) for various wind speeds. The effects of temperature variations are neglected.

TABLE 2. Specifications of the adapted Gill-type anemometer.

Parameter	Value
Threshold velocity	0.9 m s ⁻¹
Length constant	42 m
Pressure character	0.2%/Torr
Temperature character	0.25%/deg
Output format	4 pulses/rotation (40–70 mV)
Linearity	11.8 Hz m s ⁻¹
Battery voltage	±12 V
Total weight	800 g

(i) “Envelope” of wind variations (amplitude: 1–5 m s⁻¹; thickness: 100–300 m; time scale: 5–15 min) found in Fig. 6a, b;

(ii) “Isolated” gust layer (1–2 m s⁻¹; 20–50 m; 1–5 min) indicated by an arrow in Fig. 6b;

(iii) “Multiple” gust layer (1–3 m s⁻¹; 10–30 m; 0.5–2 min) indicated by arrows in Fig. 6a;

(iv) “Noisy” fluctuations (≤ 1 m s⁻¹; <10 m; <1 min) shown in Fig. 6b.

In the next subsection we shall give some preliminary examinations on whether those variations are truly wind variations or not.

b. Sounding errors

It has been determined (see, e.g., Fujii *et al.*, 1983) that a balloon can respond to any forcing longer than the neutral buoyancy period (~ 5 min). Thus, we can-

not decide in principle whether the fluctuations discussed in the previous subsection (i) were produced by wind variations of the balloon flight level or by those of the anemometric level. However, the latter may be more probable since no clear correlations with (i) were found in the tracking and barometric data. The shorter fluctuations [(ii)–(iv)] cannot be explained by responses of the balloon to wind variations.

As we have mentioned, the attitudes and motions of each gondola were continuously monitored by accurate geomagnetic and pressure sensors. The upper and lower gondolas rotated about 0.1 and 3–7 rpm, respectively, and both gondolas inclined less than 1°. Thus the data shown in Fig. 6 might be affected by the rotations, or orbital motions, of the lower gondola.

A Gill propeller does not respond to a rotation around the vertical in a rest atmosphere because of its angular character. However, when the actual wind is a constant vector and the gondola is rotating, the two components of the anemometer must detect the wind simultaneously. Since the anemometer has a time constant of the order of 10 s and a hysteresis region near the threshold velocity, and since the Gill-type propeller has a stall region near the 90° direction, the sounding wind derived by the vector sum of the outputs of two component anemometers may not be the true wind speed. Therefore, the fluctuations (iv) of scales shorter than the order of 10 s may not correspond to actual turbulent fluctuations as reported by Barat (1975, 1982).

When the gondola revolution is along an orbit around the vertical, the observed data include a bias

FIG. 6. Microscale vertical profiles of the horizontal wind speed (relative to the balloon) obtained by the adapted Gill-type anemometers in the September 1982 flight. Multiple and isolated layers of gusts (denoted by arrows) are typically shown in (a) and (b), respectively. The wind speeds are not corrected for the temperature variations.

due to its tangential velocity. From the gondola attitude data, the maximum radius of the orbit should be less than $600 \text{ m} \times \sin(0.1^\circ) \approx 1 \text{ m}$, so that the maximum false velocity becomes $2\pi \times 1 \text{ m} (10 \text{ s}) \approx 0.6 \text{ m s}^{-1}$. We find that this bias is less than the threshold velocity, 0.9 m s^{-1} . Therefore, the fluctuations (ii) and (iii) could not be produced by sounding errors owing to the gondola rotation.

One may wonder, conversely, whether the very kind of wind variations we classify in (ii) and (iii) cause a forced oscillation of the balloon-gondola system. However, as shown in appendix B, the wind drag on the lower gondola due to fluctuations (ii) and (iii) is very small, and the time scales of these fluctuations do not correspond to any of three normal periods of the balloon-gondola system. In fact, no data of the relative wind, attitude and pressure show such fluctuations growing to great amplitude. Also, there was no correlation between the occurrence of them and the distance from the gondola, which defines the eigenfrequencies. Therefore, we consider that the gusts, (ii) and (iii), are true atmospheric phenomena.

c. Discussions of results

The occurrence of two types of gusts was reported by Yamanaka and Tanaka (1984a,c) in their discussion of the gravity-wave breaking process. It seems reasonable to consider that the multiple gust layers (iii) are local unstable zones within a gravity-wave breaking layer. If so, the breaking layer may correspond to the envelope (i), although to distinguish it from a variation of winds of the balloon flight level is somewhat ambiguous. The isolated gust layer (i) is thicker and may correspond to a vertical wavelength of breaking wave. If the fluctuations (iv) are also true, the stage shown in Fig. 6b seems to be later than that shown in Fig. 6a.

On balance, the performance of the adapted Gill-type anemometer in the actual stratospheric flight met our expectations. The design of the anemometer is optimum for balloon-borne use (see section 3). However, further studies on the balloon system are necessary in order to make the best use of the anemometer (see subsection 4b). We are going to describe the observed phenomena more precisely in another paper, connecting the data of the geomagnetic attitude sensors and pressure sensors.

5. Concluding remarks

We presented the specification of the adapted Gill-type propeller anemometer for stratospheric balloon-borne use and its application for stratospheric studies. Since gust-like phenomena may exist in the whole stratosphere, the adapted anemometer is useful for balloon observations at higher levels. As we mentioned in section 2, our plan will be fulfilled after completing the ionic anemometer, which will inform us of mi-

cro-scale turbulent fluctuations embedded among the gusts. We wish to emphasize that the adapted Gill-type anemometer is a powerful tool, also, for calibrating the ionic anemometer *in situ*, as long as rather slow and strong disturbances with gravity waves are superposed.

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APPENDIX A

Measuring Principle of Propeller Anemometer

The equation of motion for a propeller anemometer can be written as

$$I \frac{d\theta}{dt} + N = Q, \quad (\text{A1})$$

where I is the moment of inertia of the propeller, θ the angular velocity of the propeller shaft, N the moment of forces working on the shaft and Q the moment of forces working on the propeller. When the propeller rotation θ is transformed into another physical quantity E by a rotation detector, then Eq. (A1) is reduced to

$$\frac{dE}{dt} = -\alpha \rho u E + \gamma \rho u^2 - \delta, \quad (\text{A2})$$

where the terms of N and Q in Eq. (A1) are replaced by simple functions of the wind velocity u and the air density ρ . The parameters α , γ and δ are intrinsic to an anemometer and are expressed by

$$\alpha \propto \frac{d^4}{I}, \quad \gamma \propto \frac{d^3}{I} \quad \text{and} \quad \delta \propto \frac{K}{I}, \quad (\text{A3})$$

where K is the frictional torque and its physical meaning is discussed in section 3, and d is the propeller diameter.

When wind velocity is constant (denoted by $\bar{u}$), the anemometer output is also constant (denoted by $\bar{E}$). Then we obtain the following relation from Eq. (A2):

$$\bar{E} = \frac{\gamma}{\alpha} \bar{u} \left[1 - \frac{RT\delta/\gamma}{p\bar{u}^2} \right], \quad (\text{A4})$$

where we use the air pressure p for the density; R and T denote the gas constant of the air and the air temperature, respectively. If $\bar{u}$ is sufficiently large, (A4) can be written simply as

$$\bar{E} \approx \frac{\gamma}{\alpha} \bar{u} \propto d^{-1} \bar{u}. \quad (\text{A5})$$

Therefore the linearity character of a propeller anemometer is independent of the air pressure and the frictional torque.

The smaller $\bar{u}$ becomes, the more $\bar{E}$ [governed by (A4)] falls from the linear output predicted by (A5). Substituting $\bar{E} = 0$ into (A4), the threshold velocity, u_0 , for a given pressure is derived as follows:

$$u_0 = \left(\frac{\delta}{\gamma\rho} \right)^{1/2} \propto d^{-3/2} \cdot K^{1/2} \cdot p^{-1/2}. \quad (\text{A6})$$

Therefore the sensitivity of a propeller anemometer becomes lower as the air pressure decreases. In order to overcome this disadvantage in lower pressures, we must either increase the propeller diameter or decrease the frictional torque.

On the other hand, the response of a propeller anemometer can be examined by assuming $\bar{u} \approx u_0$ in Eq. (A2), of which the solution is

$$E(t) \approx \bar{E}(1 - e^{-\alpha\rho\bar{u}t}).$$

Therefore the time constant, τ , of an anemometer is written as

$$\tau = \frac{1}{\alpha\rho\bar{u}} \propto d^{-4} \cdot I \cdot p^{-1} \cdot \bar{u}^{-1}, \quad (\text{A7})$$

which implies that the response becomes less as either the air pressures or the wind velocity decreases. The distance constant, independent of the wind velocity, can be expressed as

$$\lambda = \tau \cdot \bar{u} \propto d^{-4} \cdot I \cdot p^{-1}. \quad (\text{A7}')$$

We find from (A7) or (A7)' that the response cannot be improved as long as the same propeller is used.

(A6) and (A7) are reproduced in (1) and (2) in section 3.

APPENDIX B

Oscillations of the Balloon-Gondola System

a. Free oscillation of a two-gondola balloon system

For simplicity we consider a spherical balloon in a rest atmosphere with two point-mass gondolas swinging in a vertical plane (see Fig. B1). The governing equations are

$$\begin{aligned} I_B \frac{d^3\theta_0}{dt^2} &= l_0(m_1 + m_2)g(\theta_1 - \theta_0), \\ m_1 \frac{d^2}{dt^2} (l_0\theta_0 + l_1\theta_1) &= -(m_1 + m_2)g\theta_1 + m_2g\theta_2, \\ m_2 \frac{d^2}{dt^2} (l_0\theta_0 + l_1\theta_1 + l_2\theta_2) &= -m_2g\theta_2, \end{aligned} \quad (\text{B1})$$

where I_B is the moment of inertia of the balloon given by

$$I_B = \frac{2}{3} m_0 l_0^2. \quad (\text{B2})$$

The notations and quantities of each symbol are shown in Fig. B1.

An eigenfrequency, ω , for Eq. (B1) is a root of the following equation:

$$\begin{vmatrix} I_B\omega^2 - l_0(m_1 + m_2) & l_0(m_1 + m_2)g & 0 \\ l_0m_1\omega^2 & l_1m_1\omega^2 - (m_1 + m_2)g & m_2g \\ l_0m_2\omega^2 & l_1m_2\omega^2 & l_2m_2\omega^2 - m_2g \end{vmatrix} = 0. \quad (\text{B3})$$

From (B3) and (B2) we obtain

$$\begin{aligned} &\frac{2}{3} L_1 L_2 M_1 (M_1 + M_2) Y^3 - (M_1 + M_2) \\ &\times \left[\frac{2}{3} (L_1 + L_2) + L_2 (1 + L_1) M_1 \right] Y^2 \\ &+ \left[\frac{2}{3} + (1 + L_1 + L_2) (M_1 + M_2) \right] Y - 1 = 0, \end{aligned} \quad (\text{B4})$$

where

$$\begin{aligned} L_1 &= \frac{l_1}{l_0}, \quad L_2 = \frac{l_2}{l_0}, \quad M_1 = \frac{m_1}{m_0}, \\ M_2 &= \frac{m_2}{m_0} \quad \text{and} \quad Y = \frac{m_0 l_0 \omega^2}{g(m_1 + m_2)}. \end{aligned} \quad (\text{B5})$$

Equation (B5) has three real roots for the given L and M values. Here L_2 is the variable parameter during the

FIG. B1. Calculated free-oscillation periods of the balloon gondola system used in the September 1982 flight. Solid curves I–III denote the three normal modes (two gondolas). A dashed curve shows the case of a simple pendulum oscillation. The observed gondola rotation period is shown by a thick arrow. Time scales of the observed wind variations (ii)–(iv) are shown by thin arrows. Theoretical notations of the system are also indicated.

lower gondola reeldown, and the others are all constant. The three branches of the normal periods, $T = 2\pi/\omega$, are numerically obtained as shown in Fig. B1. When the distance of the lower gondola below the upper one is 600 m, the normal periods are 3, 12, and 42 s. The fluctuations (iv), mentioned in section 4, are quite similar to the former two modes. However, (ii) and (iii) do not correspond to the last mode, since the normal period should be strongly dependent on the distance between the gondolas.

b. Wind drag

Displacements that cause oscillations of the lower gondola result from wind drag on the balloon or the gondolas. According to the data shown in Fig. 6, the maximum wind variation, Δu , is about 5 m s^{-1} . Thus the maximum wind drag can be estimated as

$$C_D S \rho (\Delta u)^2 / 2 \approx \begin{cases} 30 \text{ N} & \text{(for the balloon)} \\ 0.1 \text{ N} & \text{(for the lower gondola),} \end{cases} \quad (\text{B6})$$

where ρ is the atmospheric density ($\approx 4 \times 10^{-2} \text{ kg/m}^3$), C_D is the drag coefficient (≈ 0.2) and S is the ef-

fective surface area ($\approx$ the cross-sectional area). Therefore, the wind drag on the balloon is much greater than that on the gondola.

This drag is considered to induce the gondola's oscillation through the wire. If we can approximate the balloon-gondola system as a simple pendulum, putting $\theta = \theta_2 \approx \theta_1 \approx \theta_0$, Eq. (B1) is rewritten as follows:

$$\left. \begin{aligned} (m_0 + m_1)(l_0 + l_1 + l_2) \frac{d^2\theta}{dt^2} &= C_D S \rho \frac{(\Delta u)^2}{2} + m_2 g \theta \\ (l_0 + l_1 + l_2) \frac{d^2\theta}{dt^2} &= -g\theta \end{aligned} \right\} \quad (\text{B7})$$

The first equation of Eq. (B7) means the rotation of the balloon around the lower gondola. Eliminating l 's in Eq. (B7), we can easily obtain the maximum oscillation angle as

$$\theta_{\max} \approx \frac{C_D S \rho (\Delta u)^2}{2(m_0 + m_1 + m_2)g}. \quad (\text{B8})$$

We observed the inclination of the lower gondola using the geomagnetic sensor (see section 4). According to the data, $\theta_{\max} < 0.1^\circ$, so that the effective wind fluctuation becomes $\Delta u < 1.5 \text{ m s}^{-1}$. The average of the wind variations shown in Fig. 6 is consistent with this estimation. Also, this result implies that the adapted Gill anemometer cannot detect most of the gondola pendulum oscillations. Therefore, we can consider that the pendulum oscillation due to the wind drag cannot stray into the stronger wind variations, (ii) and (iii) described in section 4.

c. Enforcement of rotation

The wind drag force also has a tangential component and causes a balloon rotation. When the rotation angle is φ , we can write, approximately,

$$I_B \frac{d^2\varphi}{dt^2} = C_F S \cdot \frac{1}{2} \rho (\Delta u)^2 \cdot l_0,$$

and the angular velocity is given by

$$\frac{d\varphi}{dt} = \frac{3 C_F S \rho (\Delta u)^2}{4 m_0 l_0} t, \quad (\text{B9})$$

where C_F is the frictional drag constant ($\approx 0.5 C_D$). From (B7) and (B8) we find a relationship between the swinging angle and the rotation speed, as follows:

$$\left| \frac{d\varphi/dt}{\theta_{\max}} \right| = \frac{C_F \cdot (m_0 + m_1 + m_2) g \cdot \tau_D}{C_D \cdot 2 m_0 l_0}, \quad (\text{B10})$$

where τ_D denotes a characteristic time scale of the wind drag.

According to the observed results (section 4), $\theta_{\max} < 0.1^\circ$ and $|d\varphi/dt| = 3\text{--}7 \text{ rpm}$ for the lower gondola.

Then we have $\tau_D > 3.5\text{--}8$ min. This result is quite reasonable, when we remember that a balloon can respond to wind variations longer than the neutral buoyancy period.

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