An Ultrasonic Altitude-Velocity Sensor for Airplanes in the Vicinity of the Ground

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This paper shows the possibility of an ultrasonic sensor which detects the altitude and the vertical velocity of an airplane in the vicinity of the ground. The principle of the present technique depends on the measurement of time in which the ultrasonic wave propagates the distance between the airplane and the ground, because the sonic velocity is approximately constant at the usual atmospheric temperature. Furthermore, by differentiating the altitude signal with respect to time, it is also possible to detect the vertical velocity of the airplane. The fundamental performances of this sensor, i.e. the detectable altitude limit, effect of the power plant noise, effect of the attitude, slip stream and forward velocity of the airplane, effect of ground conditions and so on, are investigated with some experiments carried out in the laboratory and also by the flight tests using a helicopter and a conventional airplane.

1. Introduction

INVESTIGATIONS of the characteristics of ultrasonic wave propagation in air[1,2] led the authors to conclude that the altitude above the ground and the vertical velocity of an airplane can be found easily and accurately with application of the ultrasonic technique. Experiments have been carried out in the laboratory and flight tests to investigate the fundamental performances of an ultrasonic sensor.

The first section of this paper presents the principle of detecting the distance between the airplane and the ground, i.e. the altitude, by measuring the propagating time of an ultrasonic wave. The vertical velocity of the airplane can also be found, by differentiating the altitide signal with respect to time. The experimental results obtained in the laboratory are presented. In the next section, several fundamental characteristics which are important for the present application are discussed. The basic performances of this sensor investigated in the laboratory are also presented. In the last section, the problems which should be checked by the flight tests are pointed out, and some experimental results obtained by the flight test with a helicopter are presented.

2. Principle of Measurement

The block diagram of an experimental apparatus to measure the distance and velocity with application of the ultrasonic technique is illustrated in Fig. 1. The frequencies of the ultrasonic oscillator used in this preliminary experiment are 75, 50 and 19 kHz. The transmitter and the receiver are both $BaTiO_3$ transducers.

The principle of measurement, or the process to obtain the d.c. voltage which is proportional to the distance between the transducers and the reflector plate, is as follows[2]: since the sonic velocity is approximately constant at the usual atmospheric temperature,‡ the propagating distance of the ultrasonic wave is proportional to time in which the ultrasonic wave propagates to and fro between the transmitter and the reflector. Accordingly, the output voltage of this circuit is proportional to the distance between the transmitter and the reflector. In addition, as shown in Fig. 1, the voltage given by the differentiated value of the distance signal indicates the velocity of the transmitter relative to the reflector in this instant. For the calibration of this sensor, the position and the velocity of the reflector plate were measured mechanically and compared with the values detected with the aforementioned technique. Some experimental results are shown in Figs. 2 and 3. In those diagrams, e_v and e_v' are the output voltage of the distance and velocity, and X and V are the distance and velocity of the reflector relative to the transmitter, respectively. The diagrams show that the sensor has good linearity and small errors.

3. Fundamental Characteristics of Ultrasonic Wave Propagation in Air

Before the proposed ultrasonic sensor is used for airplanes in practice, a number of problems must be investigated. These are summarized as follows: 1) detectable altitude limit; 2) noise spectrum caused by the power plant;

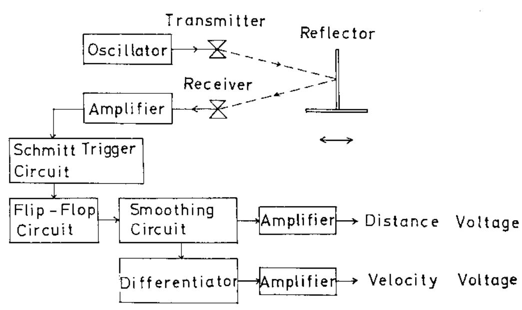

Fig. 1 Block diagram of an apparatus to measure the distance and velocity.

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‡ The sonic velocity varies in proportion to $T^{1/2}$, where T is the absolute temperature, and therefore changes roughly 10% between very cold-day and hot-day ground temperature. However, an operational sensor system could be designed to correct the error by providing a control to be set by the pilot based on the ground temperature.

3) effect of the slipstream of propellers or rotors; 4) effect of the forward velocity of airplane; 5) effect of airplane attitude; and 6) effect of ground conditions.

First of all, the detectable distance limit of this sensor can be estimated from the attenuation characteristics[1,3] of the ultrasonic wave propagation in air, which is shown in Fig. 4. From this diagram, it is obvious that the lower the frequency of ultrasonics, the longer the detectable distance will be. Accordingly, the frequency of the practical ultrasonic sensor should be chosen as low as possible, e.g. 19 kHz.

However, the frequency of ultrasonic sensor should also be determined by the noise spectrum of the powerplant of airplanes. In the case of helicopters, the noise spectrum of a helicopter rotor shows satisfactorily low-noise level at 19 kHz, and therefore it seems to be a reasonable value from this point of view, too. But, in the case of conventional airplanes, the noise level at 19 kHz is different from point to point and generally not so low even if the powerplants have propellers.

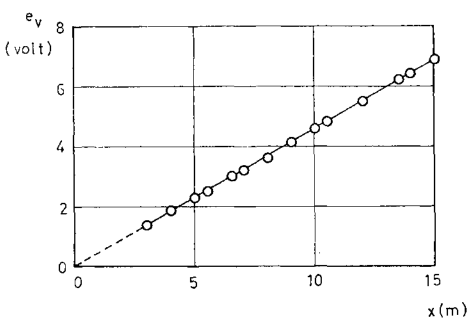

Fig. 2 Results of the measurement of distance of a reflector plate.

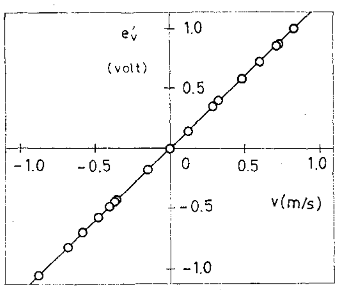

Fig. 3 Results of the measurement of velocity of a reflector plate.

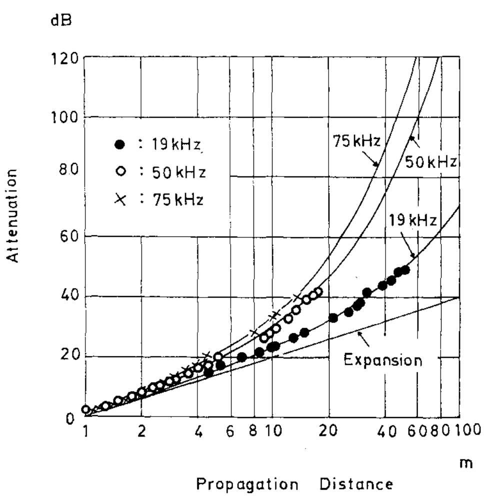

Fig. 4 Attenuation characteristics of ultrasonics in air.

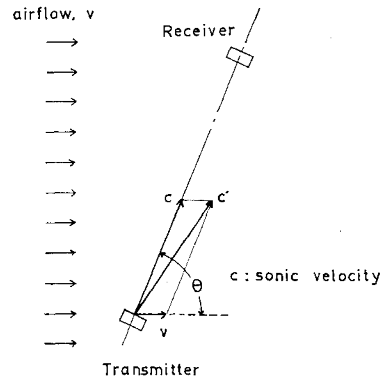

Fig. 5 Effects of the steady wind.

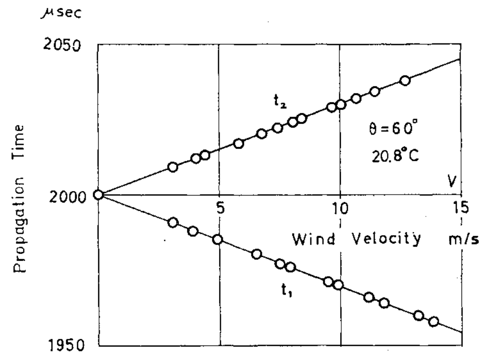

Fig. 6 Variation of the propagation time due to the steady wind.

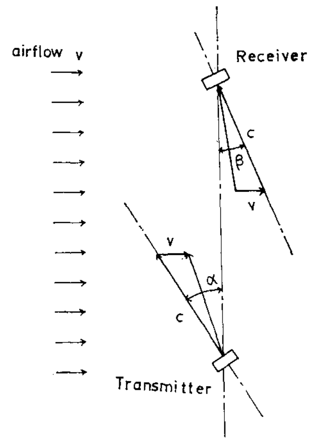

Fig. 7 Effects of the steady wind.

Therefore, in this case the attachment position and the frequency of the sensor should be chosen so as to avoid the serious effects of the powerplant noise.

The slipstream of rotors or propellers affects the direction and the velocity of ultrasonic wave propagation. Those effects have been investigated with stationary airflow in a low-speed wind tunnel,[2] and the experimental methods and results are shown in Figs. 5–8. In those diagrams, c is the sonic velocity, v is the wind velocity, α, β and θ are the inclination angles of transducers relative to the direction of airflow and p/p_0 is the ultrasonic pressure ratio measured by the receiver. From these experimental results, it is found that the sound wave propagates in the direction of the vector summation of the sound velocity, in the windless state and the wind velocity. Accordingly, it is concluded that the slipstream induces errors in altitude measurement and, in addition, induces reduction of sensitivity of the receiver. The former is due to the velocity error caused by the airflow and the latter is due to the directivity of ultrasonics. Figure 9 shows an example of the directivity function $R(\gamma)$, where γ is

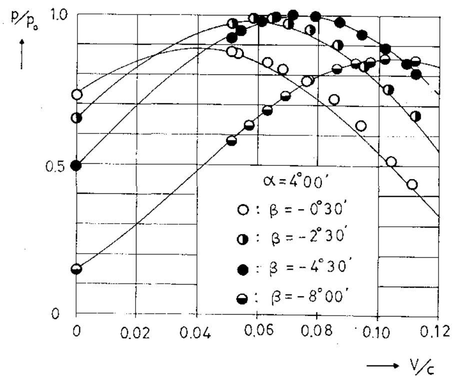

Fig. 8 Variation of the ultrasonic pressure ratio or the senstivity due to the steady wind.

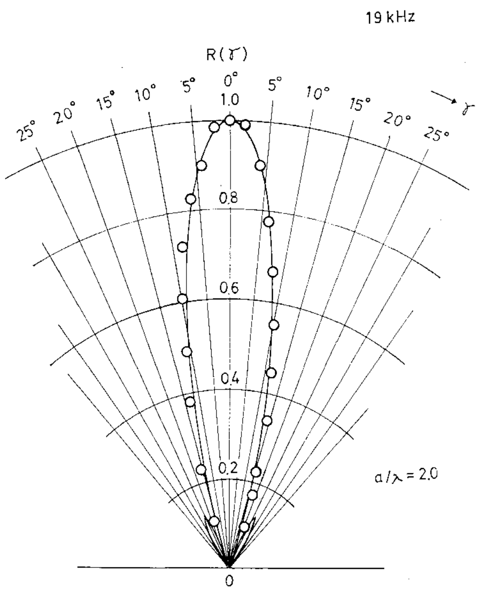

Fig. 9 Directivity of 19 kHz ultrasonics.

the inclination angle of the wave from the center line, a is the radius of circular transducer surface and λ is the wave-length.

From the same reason, the forward velocity and the attitude of the airplane induce errors in altitude measurement and also sensitivity reduction of the received wave. However, as is well-known, the higher the frequency of ultrasonics, the more acute the directivity becomes. Therefore the low-frequency wave such as 19 kHz is advantageous from this point of view, also.

Other effects, for example ground conditions and so on, were investigated in the flight tests and are stated in the following section.

4. Flight Test Results

The flight tests of this sensor have principally been carried out using a single-rotored light helicopter, Kawasaki KH-4. The instrument used in the flight test is shown in Fig. 10. A photograph of the practical attachment of this sensor is shown in Fig. 11. Since the sensor used in this experiment is a $BaTiO_3$ transducer of cylindrical type with a reflector cap, the sonic wave is reflected by the cap and is transmitted downward vertically. Accordingly, the transducer is used both as the transmitter and the receiver. The practical apparatus has two transducers arranged side by side, and the maximum output power and the frequency of this sensor are 150w and 19 kHz, respectively.

The important results obtained by the flight tests of the present ultrasonic sensor are as follows: 1) when the noise level caused by the power plant is high, i.e. S/N ratio is low, it becomes difficult to distinguish the ultrasonic signal and the noise, and therefore the detectable altitude is limited by the noise level. In the flight tests, it was found that the noise level increases approximately proportional to the rpm of the rotor in hovering flight. In the case of conventional airplanes with propellers, the effect of noise becomes more serious than in the case of helicopters. 2) The maximum altitude measured with this sensor in hovering flight is roughly 30 m. 3) Effect of the forward speed of the airplane was investigated with flight tests and it is confirmed that

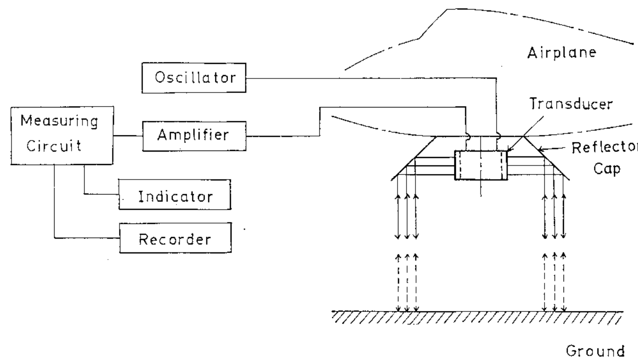

Fig. 10 Measurement of altitude at the hovering flight.

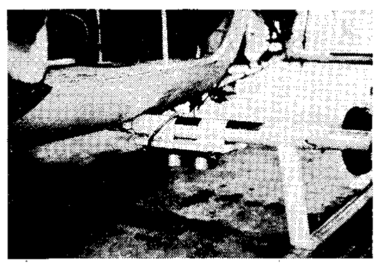

Fig. 11 Photograph of the instrument.

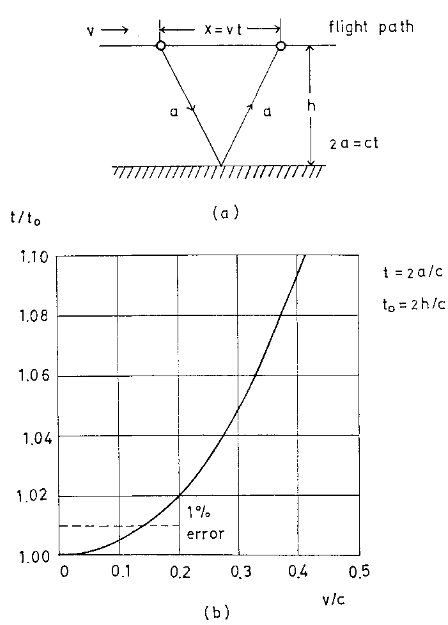

Fig. 12 Effect of the forward velocity of an airplane.

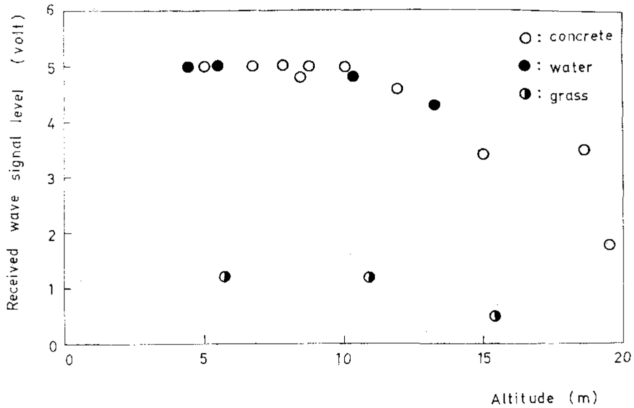

Fig. 13 Effect of the ground conditions.

these effects are small when the speed is below 130 km/h. In detail, the reflected wave signal in forward flight is approximately the same strength as that in hovering flight, and furthermore, as shown in Figs. 12a and b, the propagating time error, t/t_o, induced by the forward speed is assumed to be less than 0.5%, if the forward speed is less than 100 km/h. (i.e. $v/c = 0.1$). 4) Effect of ground conditions, i.e. concrete surface, grassy surface, water surface and so on, was investigated in the flight tests. As shown in Fig. 13, the signal levels reflected from the concrete surface and the water surface are roughly the same order, but those reflected from the grassy surface are much smaller, i.e. approximately $\frac{1}{4}$. Other ground conditions, for example uneveness of the ground, are also detectable with this sensor.

5. Conclusions

This paper presents the basic performance of an ultrasonic sensor which detects the altitude and the vertical velocity of an airplane in the vicinity of the ground. From the characteristics obtained by the preliminary experiments and the flight tests, the conclusions are stated as follows: 1) by the use of this ultrasonic sensor, it is possible to detect the accurate altitude above the ground when a hovering helicopter is close to the ground, e.g. below 30m high. This instrument is much simpler and less expensive than the radar altimeter. 2) By differentiating the altitide signal with respect to time, it is also possible to obtain the vertical velocity of the helicopter. 3) This instrument can also be used in forward flight, and accordingly it may be useful during takeoff and landing of conventional airplanes. Furthermore, it is expected that this sensor can be used as a sensor for an automatic landing system. 4) Although this paper shows the possibility of an ultrasonic altitude sensor for airplanes, it may also be useful for various purposes as a detector or a sensor in air within short distances.

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