An Ultrasonic Altitude-Velocity Sensor for Airplanes in the Vicinity of the Ground : I. Fundamental Characteristics

An Ultrasonic Altitude-Velocity Sensor for Airplanes in the Vicinity of the Ground I. Fundamental Characteristics

By

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This paper shows the possibility of an ultrasonic sensor which detects the altitude from the ground 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 possible to detect the vertical velocity of the airplane, too.

The fundamental performances of this sensor are investigated with some experiments carried out in our laboratory, and it is shown that the ultrasonic sensor will be useful in place of the radar altimeter, in particular at very low altitude. As an application of this sensor, the automatic control of a VTOL airplane in hovering flight is investigated by analog simulation studies.

1. Introduction

In order to improve the hovering performance and stability of VTOL airplane, it is an effective means to develop a suitable sensor which detects the accurate altitude and velocity from the ground of the airplane.

In addition, in the case of conventional airplanes, this sensor will still be useful at take-off and landing conditions, in particular as a detector for the automatic landing system.

Since the authors have investigated the characteristics of ultrasonic propagation in air[1][2] and expected that the ground altitude of an airplane can be found easily with application of the ultrasonic technique, some experiments were carried out to estimate the basic performances of the present sensor.

In the second section, the pinciple of detecting the distance between the airplane and the ground, i.e. the altitude, by measuring the propagating time of ultrasonic

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wave is presented. The vertical velocity of the airplane can also be found by differentiating the altitude signal with respect to time. The experimental results obtained in the laboratory indicate good agreement with the calculated ones.

In the third section, as an application of the present sensor, an automatic altitude control system in which this sensor is applied as a detector is investigated by a simulating system, and the effects of time lag due to ultrasonic wave propagation are particularly discussed.

Finally, the fundamental data obtained from the above-mentioned preliminary experiments are presented. The problems which must be checked by the flight test will be reported in the following paper.

2. Experimental Method and Apparatus

2.1 Principle of Measurement

The block diagram of an experimental apparatus to measure the distance and velocity by the ultrasonic technique is illustrated in Fig. 1. The frequency of the ultrasonic oscillator used in this experiment is 50 kHz and the maximum output power is 7 watt. The transmitter and the receiver are $BaTiO_3$ transducers of Langevin type and rubber-molded.

The process to obtain the D.C. voltage which is proportional to the distance is illustrated in Fig. 2. The principle of this method is as follows: Since the sonic velocity is approximately constant at the usual atmospheric temperature, the propagating distance of the ultrasonic wave is proportional to the time t in which the ultrasonic wave propagates the interval.

In addition, since the averaged voltage e_v in Fig. 2 is proportional to the distance or altitude, the voltage given by the differentiated value of e_v indicates the velocity in this instant.

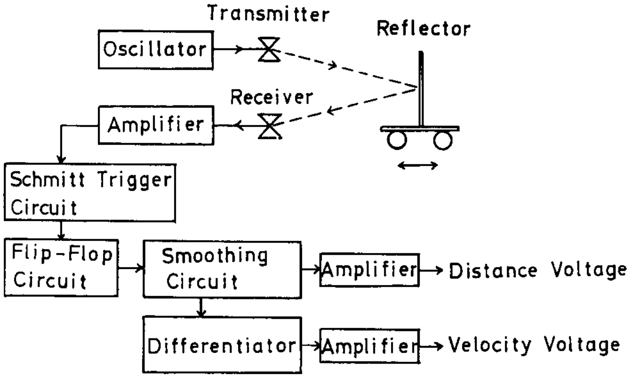


Fig. 1. Block diagram of an apparatus to measure the distance and velocity.

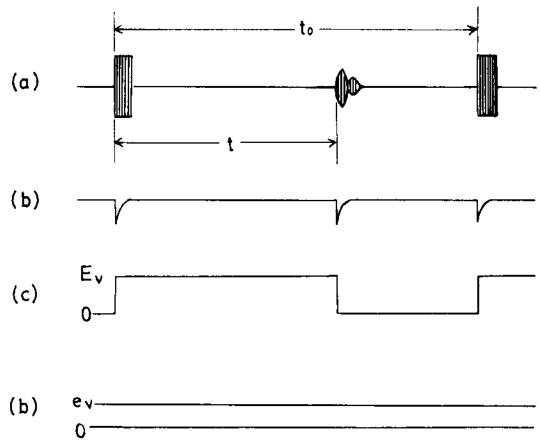


Fig. 2. Process to obtain the D.C. voltage proportional to the distance.

2.2 Experimental Apparatus

The experimental apparatus which is employed in our laboratory is diagrammatically shown in Fig. 3. A reflecting plate of this figure can be moved and the distance and velocity are measured with the above-mentioned technique.

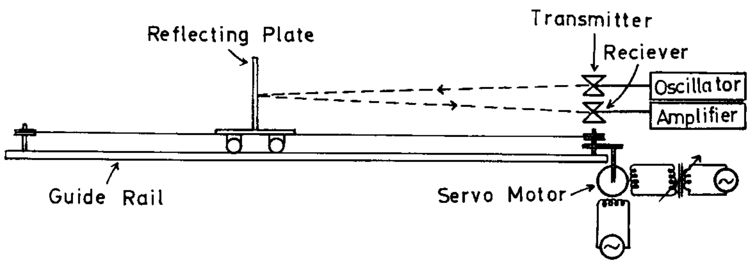


Fig. 3. Experimental apparatus to measure the distance and velocity. (This apparatus is also used to position control.)

For the calibration, the position and the velocity of this plate are detected mechanically, and those results are compared with the output voltages of this sensor. The experimental results are shown in Fig. 4 (a) and (b). It is shown that those diagrams indicate the good linearity and small degree of error, for the latter is found less than 2–3 % of the total values in those experiments.

3. Application of the Ultrasonic Sensor to a Feedback Control System

3.1 A Position Control System

As an application of this sensor, a simple position control system was investigated

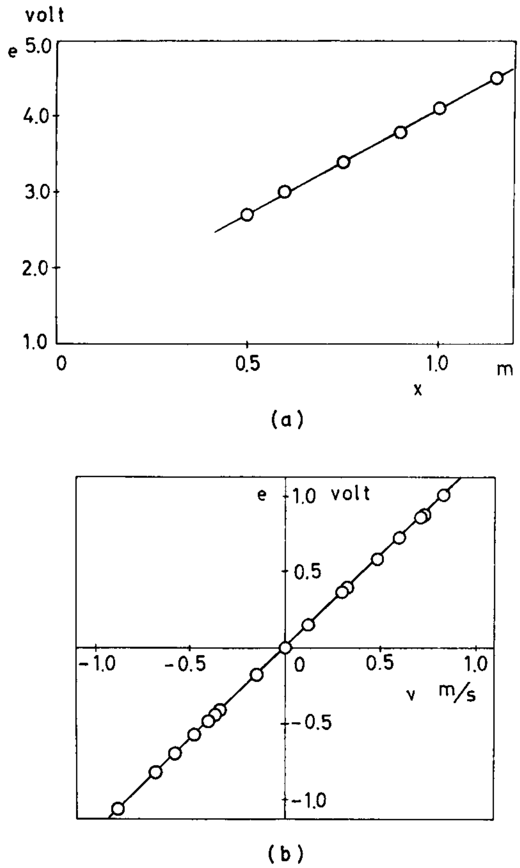


Fig. 4. Experimental results of the position and velocity.

experimentally. The apparatus used in this experiment is the same one as that of Fig.3, and the block diagram of this system is shown in Fig. 5.

Two kinds of experiments are tested; (1) a transient response motion of the reflector to a step input command, and (2) transient motions of a stationary reflector due to small disturbances. Several examples of those experiments are illustrated in Fig. 6 and Fig. 7 respectively. In Fig. 7, K_D is the damping gain of this system

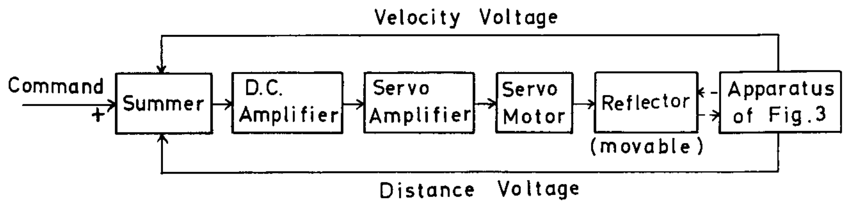


Fig. 5. Block diagram of a position control system.

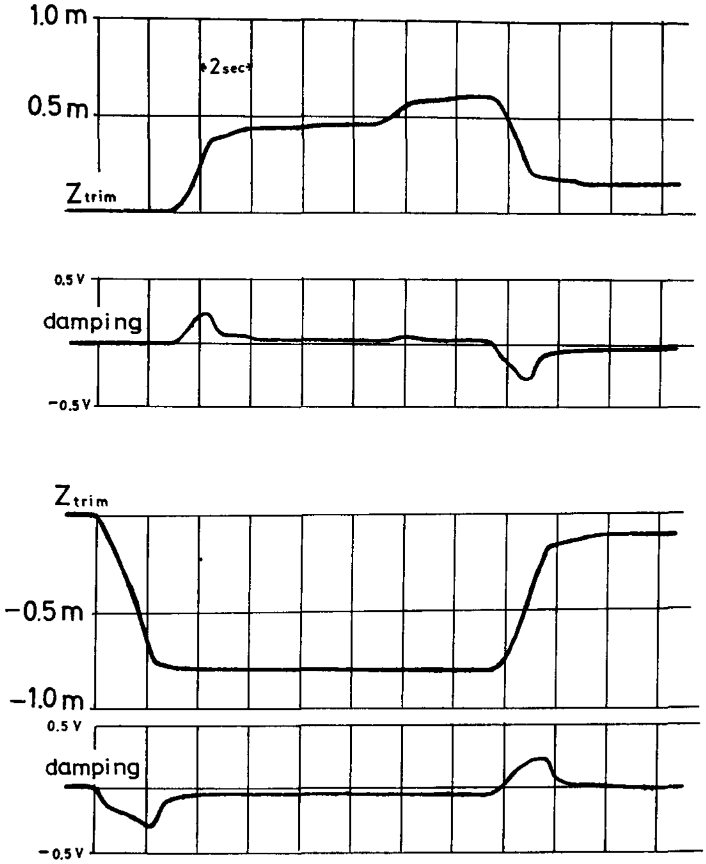


Fig. 6. Transient motions of the reflector to a step input.

and (a) and (b) show the experimental results and the calculated ones by analog simultation respectively.

Those diagrams show that the ultrasonic sensor is available as a sensing element of control systems, for example an automatic altitude control system, and the accuracy is relatively high, for the error of the above-mentioned position control is small in those examples.

3.2 Effects of Time Lag due to Ultrasonic Wave Propagation

It is a well-known fact that the sonic velocity varies with the temperature, but it is approximately 340 m/s at the usual atmospheric condition. Accordingly, when the ultrasonic wave is used for detecting the distance, effects of time lag of ultrasonic signal caused by the finite propagation velocity should be taken into consideration, for it takes approximately 6ms. to propagate the distance of 1 meter. Those effects

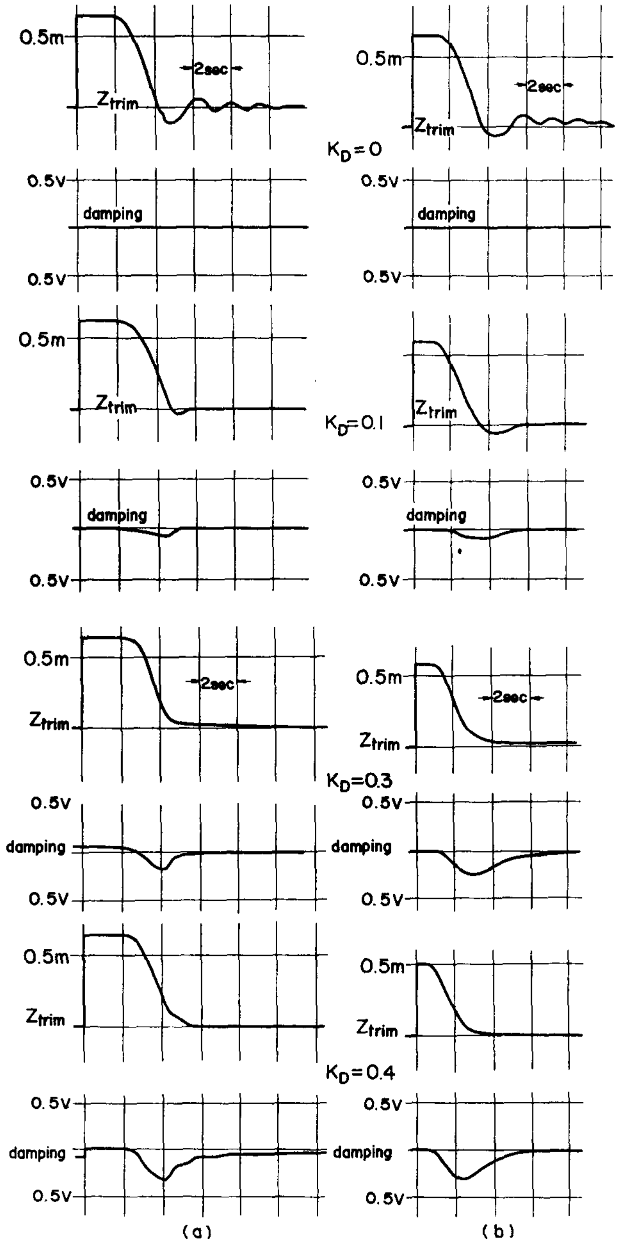


Fig. 7. Transient motions of the reflector.

become increasingly important when the propagating distance increases.

The influences are studied with an analog simulation system, which is approximated by a circuit given in Fig. 8. In this block diagram, the transfer function of

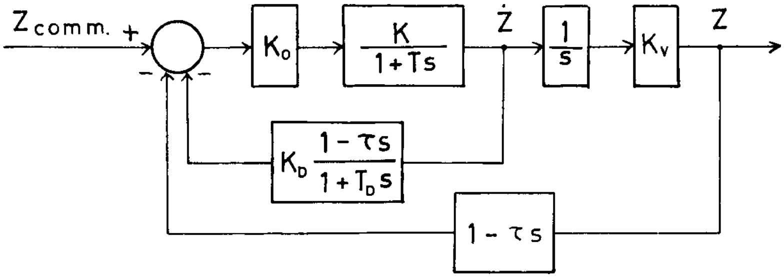


Fig. 8. Analog simulation system of a position control circuit which includes the ultrasonic sensor.

this ultrasonic sensor is expressed by $1-\tau s$, because the time constant τ is small and, therefore, the approximate formula

$$e^{-\tau s} \fallingdotseq 1-\tau s$$

is introduced, and K_0 is the gain of the servo amplifier.

Several examples of the transient response of this system are shown in Fig. 9. In comparison with Fig. 7 (b), in which the effect of time lag was neglected, it is obvious that the damping of the response motion looks smaller.

The characteristics of this system can be discussed by the root locus method as follows: since the loop transfer function of this system is expressed by

$$G\cdot H = -\frac{K_0\cdot K(K_D+K_V\cdot T_D)\tau}{T\cdot T_D}\cdot\frac{\left(s+\frac{1}{K_D/K_V+T_D}\right)\left(s-\frac{1}{\tau}\right)}{s(s+1/T)(s+1/T_D)}$$

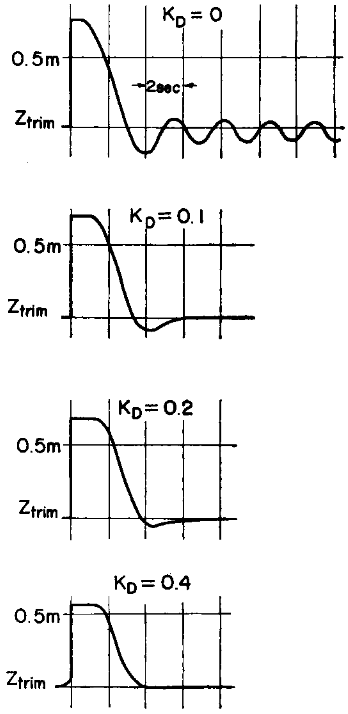


Fig. 9. Results of analog simulation.

The root-loci of this system are illustrated in Fig. 10.

From those diagrams, it is found that, when the time constant τ increases and then the open loop gain increases, the damping of this system becomes smaller, and in some cases oscillatory response motions will be induced.

4. Problems and Discussions on the Ultrasonic Sensor

There are a number of problems which should be checked when the present

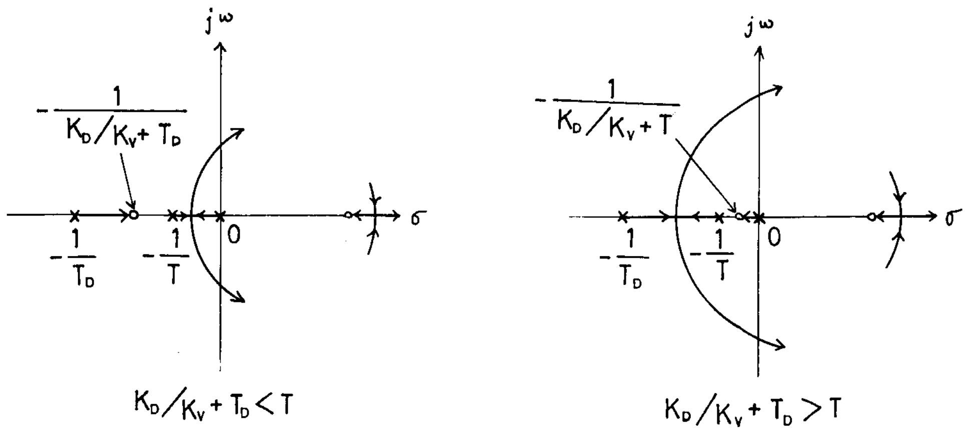


Fig. 10. Root-loci of the analog simulation system.

ultrasonic sensor is used for airplanes in practice. The principal problems are summarized as follows:

(1) Detectable altitude limit
(2) Effect of noise spectrum of the power plant
(3) Slipstream effect of the power plant
(4) Effect of airplane attitude
(5) Effect of forward speed
(6) Ground conditions
(7) Detection of small obstacles

Among those problems, the detectable distance limit of this sensor is strongly related to the attenuation characteristics of the ultrasonic propagation in air, which is shown in Fig. 11. From this diagram, it is obvious that the lower the frequency of ultrasonics is, the longer the detectable distance will be. Therefore, the frequency of a practical ultrasonic sensor should be chosen. as low as possible, for example 20 kHz.

The frequency of ultrasonic sensor should also be determined by the noise spectrum of the power plant of airplanes. An example of noise spectrum of a helicopter rotor is shown in Fig.12. As the noise level at 20 kHz seems to be sufficiently low, it will be an adequate value from this point of view, too.

The slipstream effects of a helicopter rotor are investigated by the stationary airflow in a low-speed wind tunnel. The experimental apparatus and results are shown in Fig. 13 and Fig. 14 respectively. From those results, it is found that the sound wave propagates into the direction of the vector summation of the sound velocity at the windless state and the wind velocity. The reason of Fig. 14 (a), which is the case of $\theta=0°$, is supposed that the wind velocity behind the

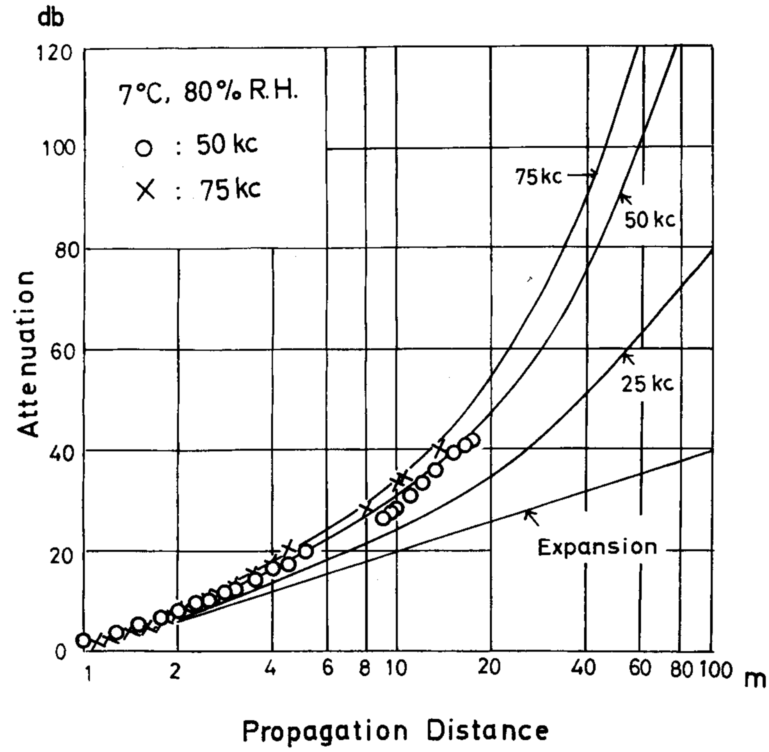


Fig. 11. Attenuation of ultrasonics.

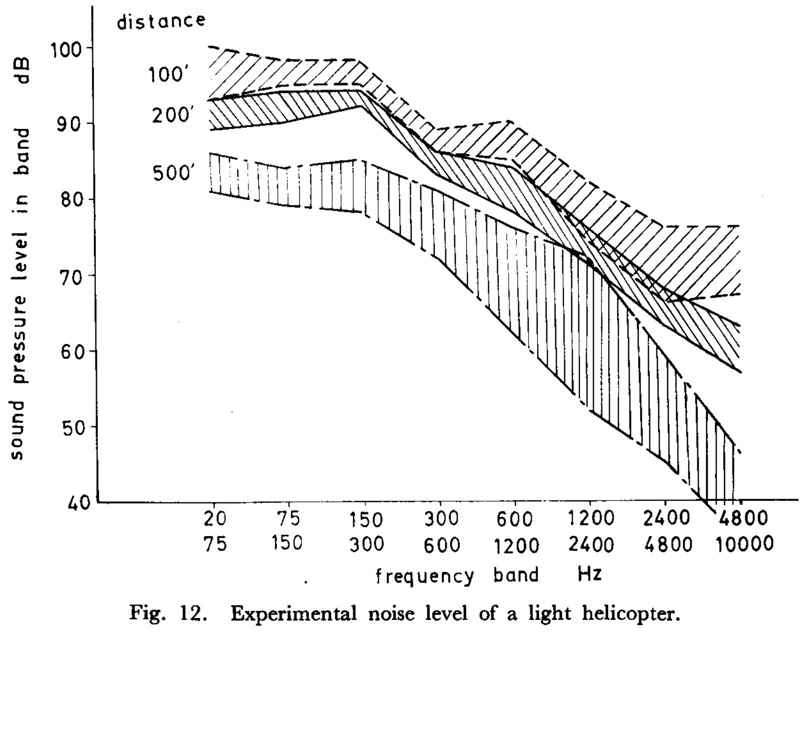
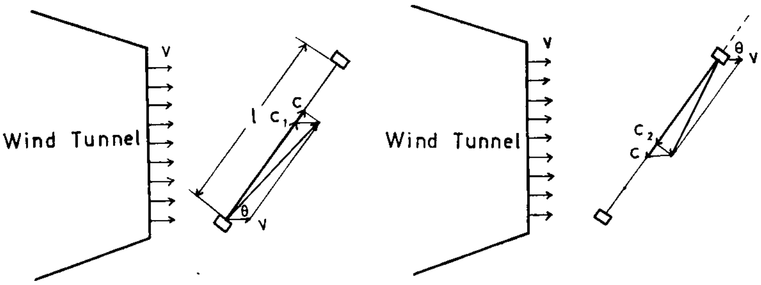


Fig. 12. Experimental noise level of a light helicopter.



$$t_1 = \frac{l}{C_1} = \frac{l}{C + V\cos\theta} \qquad t_2 = \frac{l}{C_2} = \frac{l}{C - V\cos\theta}$$

Fig. 13. Experimental apparatus of steady wind effect.

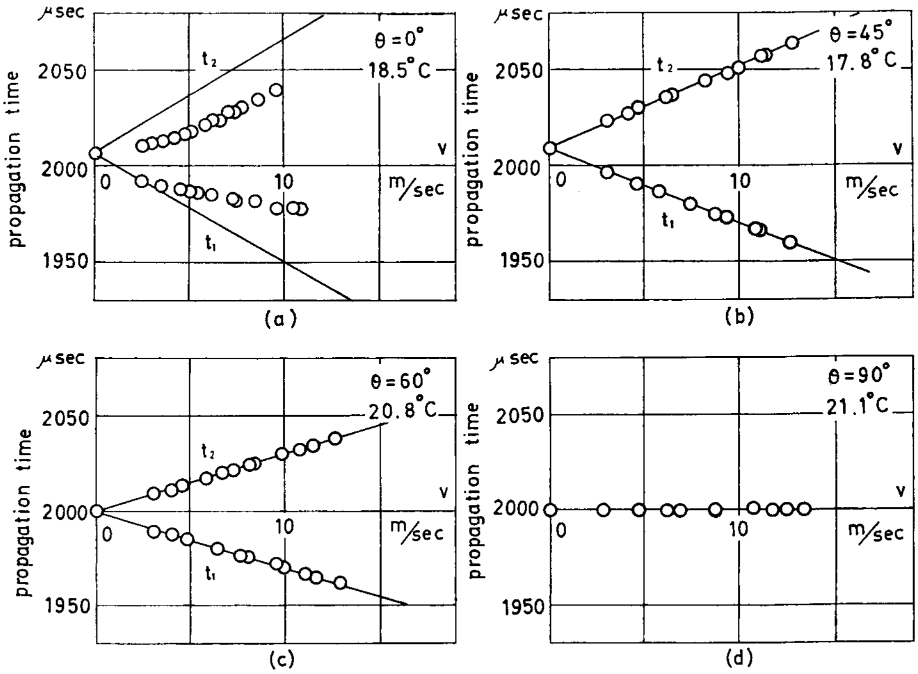


Fig. 14. Experimental results of steady wind effect. (Curves are theoretical ones.)

transducer is lower because of the wake region. Accordingly, when the rotor slipstream flows downward vertically, the influences on the ultrasonic wave propagation will be cancelled out and no effect will be induced theoretically.

Effects of airplane attitude and forward speed are principally related to the directivity of ultrasonic propagation. Since the directivity becomes acute at higher frequency, the low frequency wave such as 20 kHz is still considered advantageous from this standpoint, for the detectable region of reflected wave will be broader.

Other effects, for example ground conditions and so forth, will be investigated by flight tests with the use of a practical airplane.

5. Conclusions

This paper presents the fundamental characteristics of an ultrasonic sensor which detects the altitude and vertical velocity of an airplane in the vicinity of the ground.

The conclusions obtained from the results of preliminary experiments and simulation studies are as follows:

1) By making use of this ultrasonic sensor, it is possible to detect the accurate altitude from the ground of an airplane when it is close to the ground. This instrument is much simpler than the radar altimeter.
2) By differentiating the altitude signal with respect to time, it is also possible to detect the vertical velocity of the airplane.
3) This instrument can be used as a sensor for the automatic control systems of airplanes, though it has a weak point of time lag due to the ultrasonic wave propagation.
4) Fundamental data which are useful to the design of an ultrasonic sensor are presented in this report.

References

1), 2) H. Maeda and Y. Umeda: Characteristics of ultrasonic propagation in air. Department of Aeronautical Engineering, Kyoto University, Current Paper 12, May 1967; and 21, May 1968.