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OPTICAL TECHNOLOGY FOR FLIGHT CONTROL SYSTEMS

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16. Abstract Optical application to the flight control system including optical data bus, sensors, and transducers are analyzed. Examples of optical data bus include airborne light optical fiber technology (ALOFT), F-5E, YA-7D, MIL-STD-1553 fiber optic data bus and NAL-optic data bus. This NAL-optic data bus is applied to STOL, and its characteristics are stressed. Principles and advantages of optical pulse-digital transducers are discussed.					
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Introduction of the author

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Born in 1939, graduated from the Chuo University (Precision instrument engineering division of the Second Engineering Department) in 1966. Entered the Japan Aeronautics and Space Research Institute in 1961. Engaged in research activities on estimation of a differential coefficient of safety operation, the hydraulic control system of STOL, and FBL operation system and others. A regular member of the Japan Society for Instrumentation and Automated Control.

1. INTRODUCTION

Efficient, inexpensive, reliable, low noise and large-size airplanes have been in demand in recent years. These airplanes are also required to be economical, safe to operate, comfortable and environmentally suitable. In the flight control system that is essential in the production of airplanes described above, it is becoming increasingly necessary to apply the function of signal transmission system through the use of digital computers in place of the existing mechanical linkage as the supplementary system.

Some of the supplementary functions mentioned above include SAS (Stability Augmentation System), CAS (Control Augmentation System) and others. They are all put to practical use.

In the future, removal of the mechanical linkage (further complication of mechanization, increase in weight and non-linear characteristics due to mechanical break down, abrasion and transformation) in favour of further expansion in SAS and CAS functions is being envisioned. The current developmental trend is toward FBW (Fly By Wire) in which the control of the airplanes is done based upon the most suitable flight control data of digital computers. The switch to FBW not only changes the signal transmission system from that of the mechanical means into electric means but also make itself the essential tool in order to realize ACT (Active Control Technology) and CCV (Control Configuration Vehicle). In order to assure its dependability, FBW needs to have more prolixity in its system. In addition, development of FBL based on the optical technology is hoped for. Its research and development are actively conducted.

In this essay, optical applications to the flight control system including optical data bus, optical sensors, optical transducers whose research and development as well as actual testing have already been started sometime ago are introduced. Furthermore, future of the optical system is briefly surveyed as the conclusion of this essay.

2. BACKGROUND OF THE DEVELOPMENT OF THE OPTICAL TECHNOLOGY

When airplanes in flight are stricken by a thunderbolt, all the electric systems (electronic instruments, power source

lines, signal lines) usually receive electromagnetic induction (impulse current and induced voltage) by EMP (Electro Magnetic Pulse). In addition, electromagnetic interference take place within the stricken airplane between various electric instruments and signal lines or between electric power lines and signal lines. The electromagnetic interference causes generation of erroneous signals.

The position of the entrance of the EMP energy and the condition of the energy binding (1) are shown in Fig. 1 (a) and 1 (b). The measures to counter the impact current by EMP should include the following two: Measures to prevent the impact current from entering the airplane, particularly the airplane control system, and measures to locate all the electric instruments inside a properly shielded room. As for the measures against induced voltage and electromagnetic interference, the use of shielded lines is considered effective. Yet, these measures are not sufficient to completely stop the problem. Considering the increase in the aircraft weight due to the shielding material, measures other than shielding are hoped for.

Future airplanes are expected to be made of compound materials instead of aluminum alloy reducing the total weight of the airplane by 15 - 40 %. The same compound materials are widely used at several parts in today's airplanes, for example doors, tail wings, leading edge...etc. Future use of the same materials is expected to increase dramatically. Aluminum

alloy materials used as the materials for outer shell of today's airplanes functions as the shield (ground) reducing the influence of electromagnetic induction in the instance of lightning strike. Use of less amount of aluminum alloy or elimination of the same material means the reduction or elimination of the effect described above. Accordingly, a countermeasure is being sought after.

Since the optical system which uses fiber optics has the merits (2)(3) as listed in Tab. 1, it is extremely suitable as the countermeasure. The primary reasons for the application of fiber optics in airplane flight control system are reduced electromagnetic induction, excellence against electromagnetic interference, and ability to gain electric insulation.

The optical system can be realized through the optical applications of the flight control system including sensors, transducers, a variety of computers, actuators and data bus.

Some of the items listed above, such as laser gyrocompass, have already been developed and put to practical use, while others are still being developed.

3. OPTICAL BUS (4)

3.1 Developmental process of the optical data bus

As shown in Tab. 2, a theoretical analysis of optical fiber transmission (5) through total surface reflection was developed in as early as 1910. Yet, its practical application was delayed considerably. The

development of the low loss optical fiber (20 dB/km) by Corning of USA in 1970 prompted its application to airplanes for the first time in history, and more accelerated research activities were conducted since. In 1975, low loss optical fiber, 2 dB/km, was developed, and in as early as 1979, super low loss optical fiber (0.2 dB/km) which is considered to be near the theoretical limit was developed.

Development of data bus on the other hand was started in 1968 as shown in Tab. 2 based on the needs to reduce maintenance costs, wiring space, wiring weight, noise level, line mixing and deterioration of signal. Designing specifications such as ARINC 575 (6) in 1971 and MIL-STD-1553 A (7) in 1977 have been established. After that, both 1553 and 429 have been revised.

Although no specification has been established in regard to the optical data bus, its development and testing are conducted mainly in the USA along with the specifications of the data bus mentioned above. These development and testing are conducted in order to establish applicability of fiber optics. Many of them are based on MIL-STD-1553.

Before going to the developmental process of the optical data bus, a configuration of the optical fiber link in airplane control system is explained.

3.2 Schematic of optical fiber link

The flow of signal (data) in airplane control system can be divided into three categories, [1], [2], and [3] from

the functional stanspoint (9) as shown in Fig. 2, and each one is linked with optical fiber.

[1] Star links: Line replaceable units which are located in many positions within an airplane, such as a flight control computer, an air data computer, inertial flight control devices...etc. are linked. According to the direction given by bus control devices, each LRU: RT (remote terminal) handles transmission and reception of data. As the data bus specification, the command response system of MIL-STD-1553 is used.

[2] Cross lane links: In order to check the data used by the flight control computer which functions independent of other systems in the flight control control system consisting of the prolixity system, the cross lane link establishes a combined configuration in order to exchange data with flight control computers of different system.

[3] Point to point links: This is a link scheme which connects two points such as (5) and (6) (in Fig. 2). It does not require the direction of the bus control devices. It is the system in which various data repeatedly sent from the transmitter in a certain frequency are decoded, and only the necessaryy data are accepted. ARINC 429 is used as the data bus specification.

Research and development as well as testing of each configuration of optical fiber links have been conducted in the past. Some of the important ones are shown next:

3.3 Testing, research and development of the optical data bus

3.3.1 ALOFT (10) (Airborne Light Optical Fiber Technology)

This project was carried out by the US Navy in 1974 - 1977. This is the very first example of the test to examine the applicability of the optical fiber in the aviation field. A-7's have been used as the test aircraft. As shown in Fig. 3, the optical data bus is consisted of a central computer and five terminals. The configuration of the optical fiber links is the point to point links shown in [3], paragraph 3.2. The maximum data transmission rate is 10 Mbit/sec. Manchester code is used as the data code, and bundle fiber is used as the optical fiber. Approximately 130 hours of flight test has been completed. In addition, lightning tests on the ground also have been conducted.

3.3.2 F-5E (12)

This was developed as the joint venture of the Northrup Corporation and ITT of the USA. Using a F5-E mock up for ground testing and demonstration, the data bus specification MIL-STD-1553 was converted into the optical data bus with the least amount of modification.

As shown in Fig. 4, it is consisted of a bus control device and eight RT (terminals). The configuration of the optical fiber links is the star links shown in [1], paragraph 3.2. Its data transmission rate is 1 Mbit/sec.

Manchester code is used as the data code, and bundle fiber is used as the optical fiber.

3.3.3 YC-14 (13)

As shown in Fig. 5, this is an example of a test aircraft which uses an optical fiber in the data exchange transmission line between flight control computers which are structured in three-layered proximity system in the flight control system of the STOL military transport airplane tested by the US Air Force. Accordingly, the configuration of the optical fiber links is the cross lane links [2]. The merit in the use of the optical fiber is the fact that electric insulation can be gained. Through the exchange of data, spreading of accidents of different systems through the transmission lines is prevented, and independence of the three-layered proximity system can be maintained.

3.3.4 YA-7D (14)

This is the one that is practiced in the phase (II) of Digitac (Digital Tactical Aircraft), and the flight control system is consisted of a double-layered proximity system. Each data bus consists of a computer which has the function of a bus control device and two terminals. The configuration of the optical fiber links is the star links [1]. Besides the optical data bus, each system is provided with electric data bus. A searching device is used to select either the optical bus or the electric bus. The optical fiber uses the bundle fiber.

3.3.5 MIL-STD-1553 Fiber Optic Data Bus (15)

This is the example of research and development including design, manufacturing of a prototype and testing of the fiber optic data bus for the purpose of obtaining data on optical technology other than the data bus specification MIL-STD-1553 in the case of designing and manufacturing the fiber optic data bus. The data transmission rate is set at 10 Mbit/sec, and a nine port star coupler as well as bundle fiber are used. The configuration of the optical fiber links is star links.

3.3.6 NAL (National Aerospace Laboratory) Optical Data Bus (2)(16 - 19)

This research was conducted as a part of the research and development of the control system of the fan jet STOL being conducted by the National Aerospace Laboratory of the Japan Science and Technology Agency. The study of FBL system is conducted with the objective of applying the optical technology to the future STOL aircraft. Besides the research and development of the optical bus, research and development of optical sensor, optical transducer...etc. are being carried out.

Although the optical data bus is practiced in each one of the configuration of the optical fiber links [1], [2] and [3], it is centered by the star links [3]. As shown in Fig. 7, the optical data bus of the star links comprises a bus control device and five terminals. A flight simulator

device is connected to it as its sub system.

The characteristics of the NAL optical data bus are that it is based on MIL-STD-1553B and that it is added with the following functions:

(1) Connection between the input/output signal over the optical data bus line and the input/output signal to the sub-system is done using buffer memory (BM): RAM (Random Access Memory), and non-synchronous processing of two kinds of signal is done for the purpose of achieving higher efficiency in data transmission.

(2) Input/output signal management (BCU) to the optical data bus line is done using a micro-program which is located in the ROM (Read Only Memory). It is done so in order to achieve high speed data processing.

(3) CCB (Channel Control Block) function that is stored in RAM is used as the data bus control function in order to lessen interruption handling to the computer and achieve high speed transmission of data.

(4) Also, data transmission rate can be manually switched between 1 Mbit/sec and 2 Mbit/sec. Furthermore, data transmission up to 512 words per a message can be accomplished. Also, a method known as the broadcast transmission through which a terminal device can be designated is possible. As the star coupler, a transmission condensing type star coupler is being developed. Single fiber is used instead of the bundle fiber which has been studied in the US

up to now.

Said optical data bus has already been completed. Evaluation tests are being conducted at this time.

3.4 Development of the optical branching and coupling device (star coupler)

In the development of the optical data bus based on the data bus specification MIL-STD-1553, the center core of the optical component is the star coupler. Star coupler system in general has two types - the transmission type and the reflection type. The transmission type is further classified to the condensing type (16) which uses a micro-lens and a reflective surface, the composite type (20) which uses a mixing rod and the polymer type (21) which is the improved version of the composite type.

Tab. 3 shows the optical branching and coupling characteristics of the star coupler which has been made public up to now. The polymer type is the most efficient. The insertion loss of the star coupler is -3 to 6 dB, and the fluctuation by each channel ranges between -2 and 3 dB. In designing the future optical data bus system, it is a good idea to consider the figures shown in Tab. 3.

3. OPTICAL SENSOR • TRANSDUCER

4.1 Optical sensor

The most important of all the sensors is an inertial navigation device by which airplane position, speed and

attitude angle can be obtained. In the past, the same device used to measure the angle speed using a gyroscope and maintain a level flight using the signal obtained from the gyroscope. A variety of additional information is obtained by processing the signal of the acceleration gauge which is attached to the same platform.

In recent years, development of the digital technology as well as the ring laser gyroscope which uses laser beams helped to put the IRU (Inertial Reference Unit) into practical use. This device is installed in Boeing 767's and the prototype of NAL STOL. One of the characteristics of this device is the high degree of dependability due mainly to the absence of moving parts. Only problem with this device is that it has a range of non-sensitive area at the low angle domain caused by the lock-in phenomenon. In order to solve this problem, research and development of the optical fiber gyro are actively conducted. Details of these activities are omitted since the literature shown in (22) describes the detailed information on the research and development activities.

The other method to solve the lock-in phenomenon includes the recently introduced four-mode differential laser gyro (23). Its development is watched.

Other optical sensors include the optical speed sensor, the optical acceleration sensor and the optical pressure sensor...etc. Development of these sensors are

promoted mainly by the US military organizations.

For the purpose of measuring the vibration wave form of turbine rotational fans of jet engines, a device (24) consisting of a plural number of optical sensors and data processing parts is conceived. Research and development of the device are presently conducted at NAL. The device measures the vibration waveform of rotational fans which greatly influence the jet engine propulsion. Its theoretical background is as shown in Fig. 8. Detectors made of optical fibers which receive the reflective beams are prepared around the rotational fans. Each time a rotational fan passes the detector, reflective beams are detected. The vibration waveform is calculated from the measurement of the passage time of each detector.

4.2 Optical transducer

The optical transducer which directly converts mechanical input signal (linear displacement or rotary angle) into optical signal traditionally has two types as shown in Fig. 9 - the absolute system and the incremental system. The former has the advantage of being able to directly obtain parallel digital output signal from the code plate which has the coded output according to the rotational angle of the input rotational axle. The shortcoming of the same device is that interface with other devices becomes more complicated because of the parallel output.

The latter counts the number of optical transmission

and breaking which changes in proportion to the variation of the input rotational angle, adds or subtracts it based on the standard (base) point, and calculates digital signals. Although it is easy to establish interface with other devices, it has the following shortcoming. Output cannot be calculated unless an input rotational angle is provided (the problem of the initial figure). Furthermore, erroneous detection could be accumulated.

It is more suitable to use the former as the optical transducer for aircraft use because of the problem of the initial figure seen in the latter. Yet, considering the changes that must be made to make the transducer a multiplex system in order to assure the highest degree of dependability, the parallel output signals with extremely large number of signal lines were found to have some problems in the suitability as far as interface was concerned.

Lately, an optical pulse type digital transducer (25)(26) has been introduced as a means to solve the problems related to interface described above. Its research and development are being conducted at NAL. The theoretical background is as shown in Fig. 10. Continuous beams which have been in use as the light source to the code plate are changed into optical pulse with a certain gap in time. By optically joining the parallel optical output signal after the transmission and breaking by the code plate, optical signals corresponding each bit signal are converted into time-divided

series optical output signals. From the functional standpoint connection with other devices becomes possible with one optical fiber.

There are two methods to generate the optical pulse that is shifted by a certain time gap and that is used as the light source. One is through the electric circuit, and the other is through the difference in the length of the light passage of the optical fiber.

In the case of the latter, the time gap T is given by the following formula:

$$\begin{aligned} T &= T_0 + l / v \\ &= T_0 + ln / C \\ &\approx T_0 + 5 \times 10^{-9} l \end{aligned}$$

[Note] l : length of the optical fiber, v : speed of light (within substance), n : refractive rate (substance), C : speed of light (in vacuum)

Accordingly, time gap, approximately 0.1 microsecond, can be gained at $l = 20$ m. Incidentally, dynamic error by T can be contained within one digit if the light source pulse rate that is obtained in reverse proportion to the time gap T is set higher than the angle speed of the input rotational axle and if the gray code is used as the code plate. The merits of the optical pulse type digital transducer as shown in Tab. 4 are numerous in addition to the interface. Accordingly, it is expected to be promising in the future.

5. CONCLUSION

Background information concerning the optical technology being developed for the flight control system of airplanes and research and development of the optical system consisting of the optical data bus, optical sensor, optical transducer...etc. have been introduced.

Since the optical system is least affected by lightning and electromagnetic interference, it is expected to take the place of the commonly used electric wiring. Some of the optical system, eg. laser gyro...etc. have already been put to practical use, and others are in the stage of research and development. It will not be too far for them to be put to practical use.

Optical actuators (26)(27) and optical computers (optical components) that can be driven only by oil pressure and optical signal are also at the stage of research and development. They will be also put to practical use closely following the optical system described above.

The function of the future aircraft flight control system will be carried out exclusively by the optical system which replaces the existing electric wiring. As the needs for energy-saving are increased, development of composite function instruments which receive output signals by emitting light source as needed as seen in the case of the optical pulse type digital transducers will become more significant.

This concludes the essay on the research and development as well as the future outlook of the optical technology that can be applied to the flight control system.

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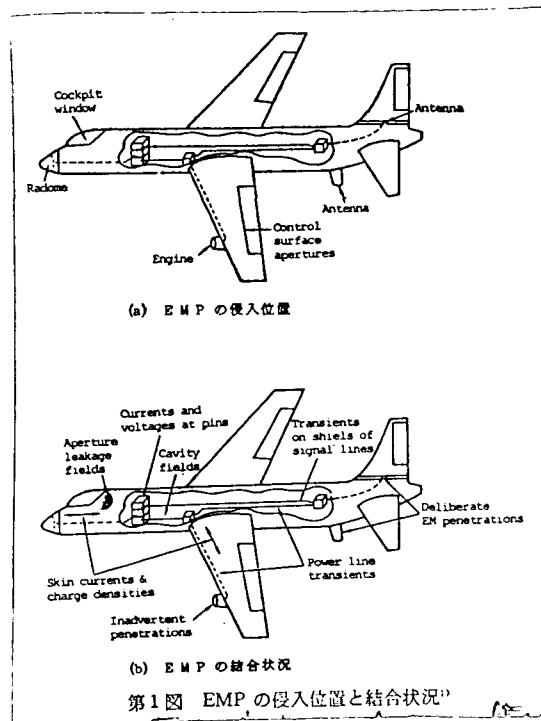
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Tab. 1 Merits of fiber optics (2)(3)

- (1) Improved signal leakage
- (2) Reduction in weight and size
- (3) Elimination of line crossing, EMI and EMP.
- (4) Elimination of copper lines

- (5) Prevention of short circuit
- (6) Elimination of the ground loop
- (7) Improved heat-proof quality
- (8) Elimination of spark and explosion
- (9) Wide band quality
- (10) Elimination of corrosion

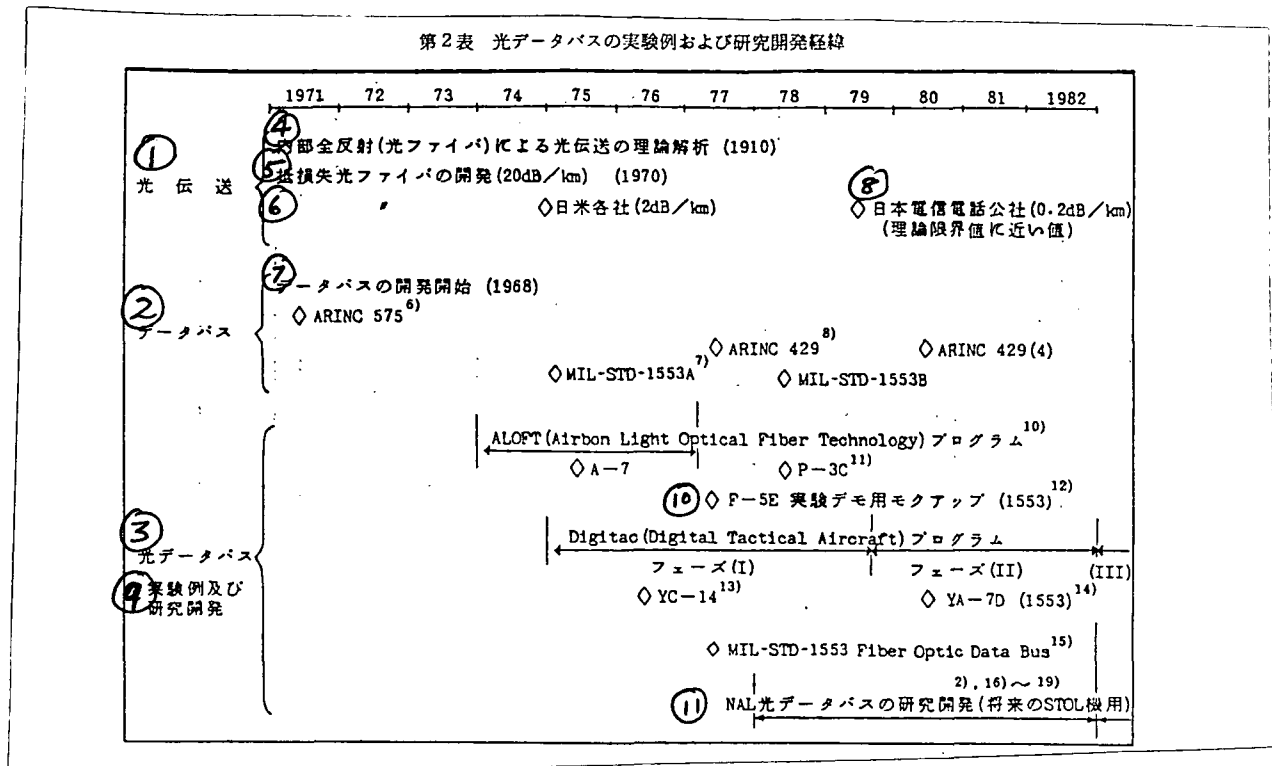
Fig. 1 Position of entrance of EMP and the condition of the coupling (1)



(a) Position of the entrance of EMP (b) Condition of the coupling of EMP

Tab. 2 Testing examples of optical data bus and the process of the research and development activities

第2表 光データベースの実験例および研究開発経緯



1. optical transmission
2. data bus
3. optical data bus
4. theoretical analysis of optical transmission by the inner total reflection (optical fiber)
5. development of low loss optical fiber
6. development of low loss optical fiber, many companies in the US and Japan
7. start of the development of the data bus
8. Japan Telephone and Telegraph Agency (close to the theoretical limit)
9. examples of experimentation and R & D
10. F-5E mock up for testing and demonstration
11. R&D of NAL data bus (for the future STOL)

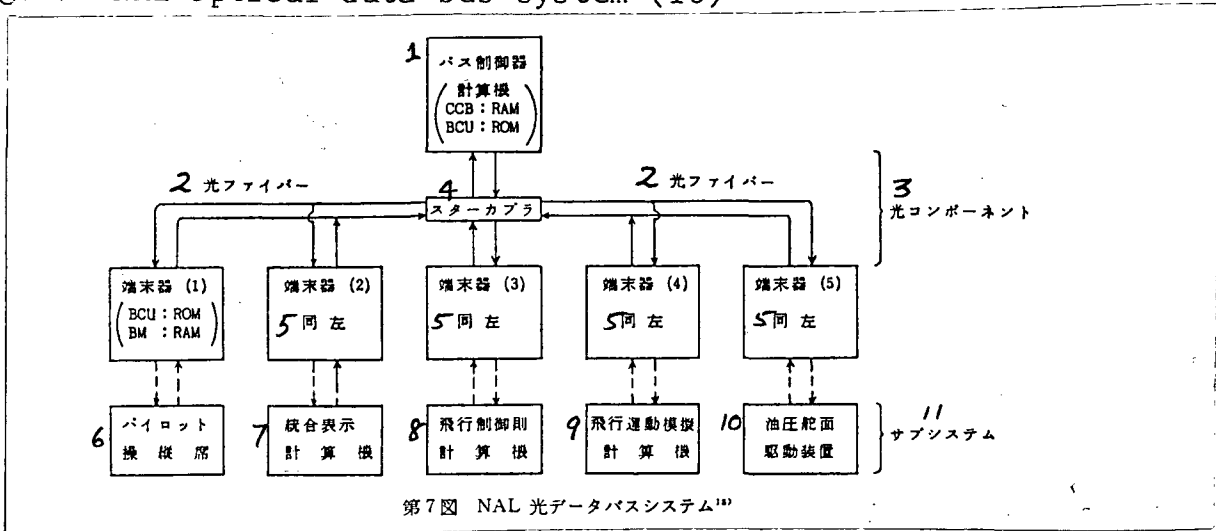
Tab. 3. Comparison of light deterioration characteristics of each star coupler (dB)

第3表 各スターカプラの光減衰特性比較 (dB)

① 種類	② 特性	③ 理論値	④ 平均値	⑤ 最大値	⑥ 最小値	⑦ 損失
⑧ F-5E (9対9, 混合透過型)***		-9.54	-16	-18.1	-13.9	-6.46
⑨ MIL 拡張 (9ポート, 混合反射型)***		-9.54	-13.98	-15.04	-13.25	-4.44
⑩ NAL (8対8, 集光透過型)***		-9.0	-12.8	-14.8	-11.7	-3.8
⑪ NAL, NEC (8対8, 混合透過型)***		-9.0	-12.7	-15.15	-12.29	-3.7
⑫ Polymer (6対6, 混合透過型)***		-7.78	-10.38	-11.58	-9.18	-2.6

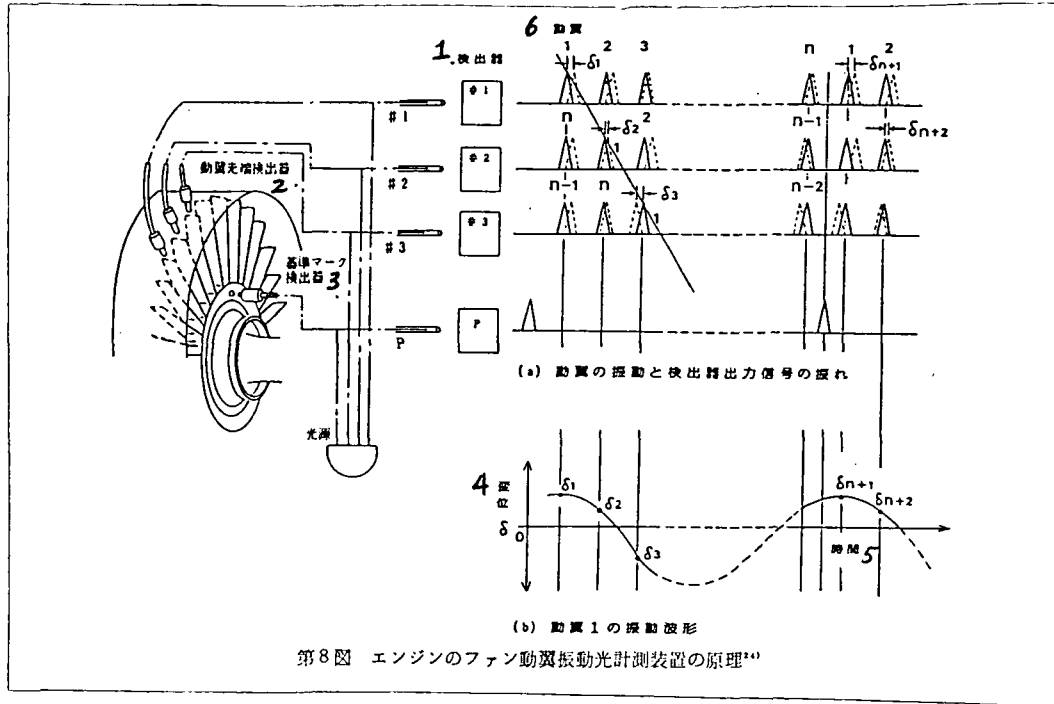
1. kind 2. characteristics 3. theoretical figures 4.
average 5. maximum 6. minimum 7. loss 8. F-5E (9 - 9,
composite transmission type) 9. MIL expansion (9 ports,
composite reflective type) 10. NAL (8 - 8, condensing
transmission type) 11. NAL, NEC (8 - 8, composite
transmission type) 12. Polymer (6 - 6, composite
transmission type)

Fig. 7 NAL Optical data bus system (18)



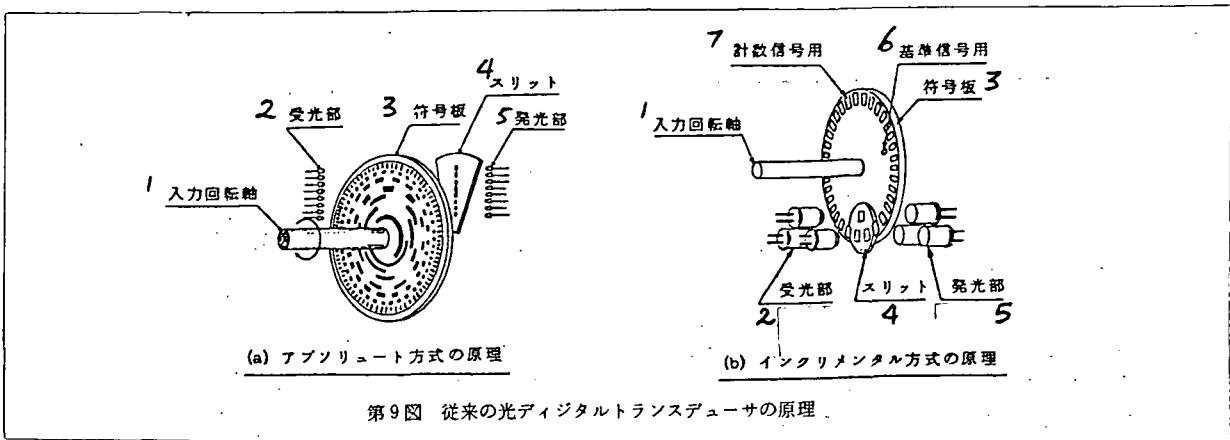
- (1) terminal (2) terminal (3) terminal (4) terminal
(5) terminal 1. a bus control device (computer CCB: RAM
BCU:ROM) 2. optical fiber 3. optical component 4. star
coupler 5. same as the left 6. pilot's seat 7. total
display computer 8. flight operation computer 9. flight
motion simulation computer 10. hydraulic driving device
11. sub system

Fig. 8 Theory of optical measurement device of vibration of fans



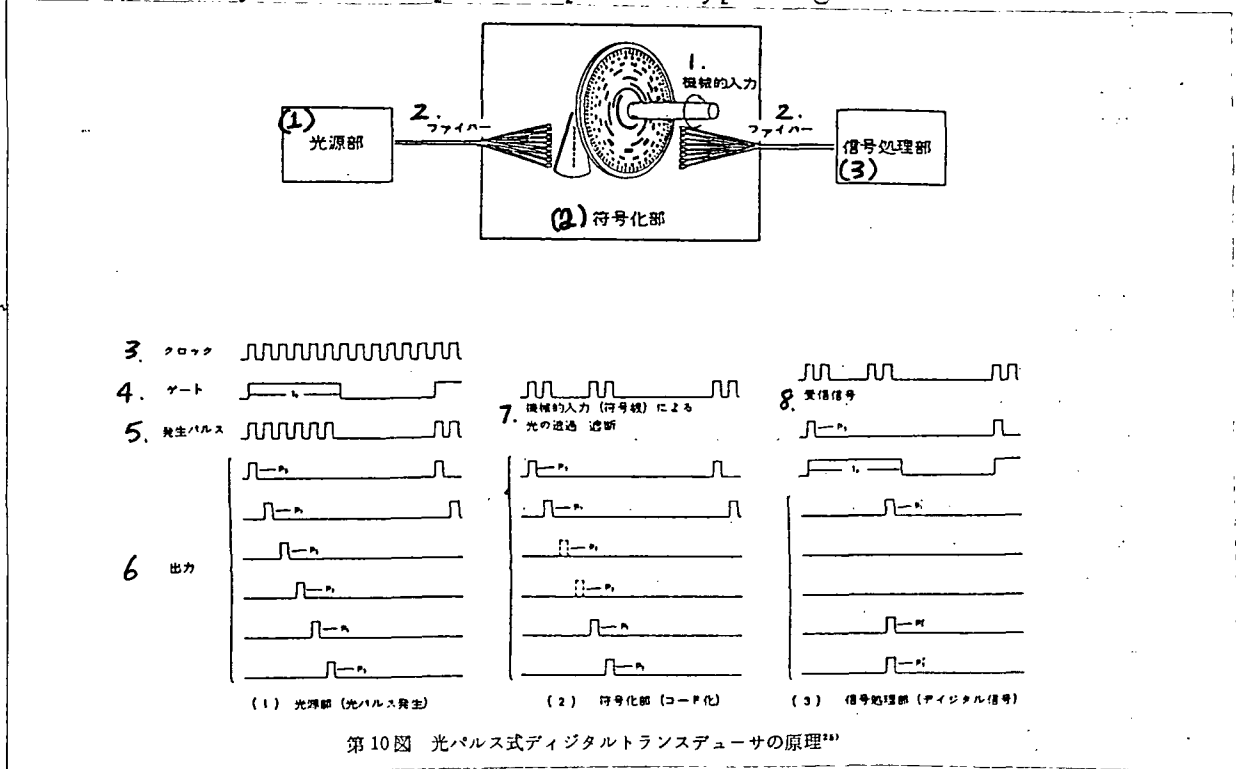
(a) vibration of the fans and the output signal of the detection device (b) vibration waveform of the moving fan 1. detection device 2. detection devices at the tip of the moving fans 3. detection device of the standard mark 4. fluctuation 5. time 6. moving fans

Fig. 9 Theory of the existing optical transducer



1. input rotational axle 2. light reception part 3. a code plate
plate 4. a slit 5. light generation part 6. for the
standard signal 7. for the counter signal

Fig. 10 Theory of the optical pulse type digital transducer



- (1) light source (light pulse generation) (2) coding part
(3) signal processing part (digital signal) 1. mechanical
input 2. fiber 3. clock 4. gate 5. generated pulse
6. output 7. optical transmission and breaking by
mechanical input 8. reception signal

Tab. 4 Merits of optical pulse type digital transducer (25)

- (1) Very easy coupling with other devices
(2) Hardly influenced by lightning and electromagnetic

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interference

- (3) Miniaturization of the coding part is possible.
- (4) A wide range reduction in electric consumption
- (5) Power upgrading of light source pulse is possible.
- (6) Increased life
- (7) All the merits of the absolute system are possible.

Fig. 4

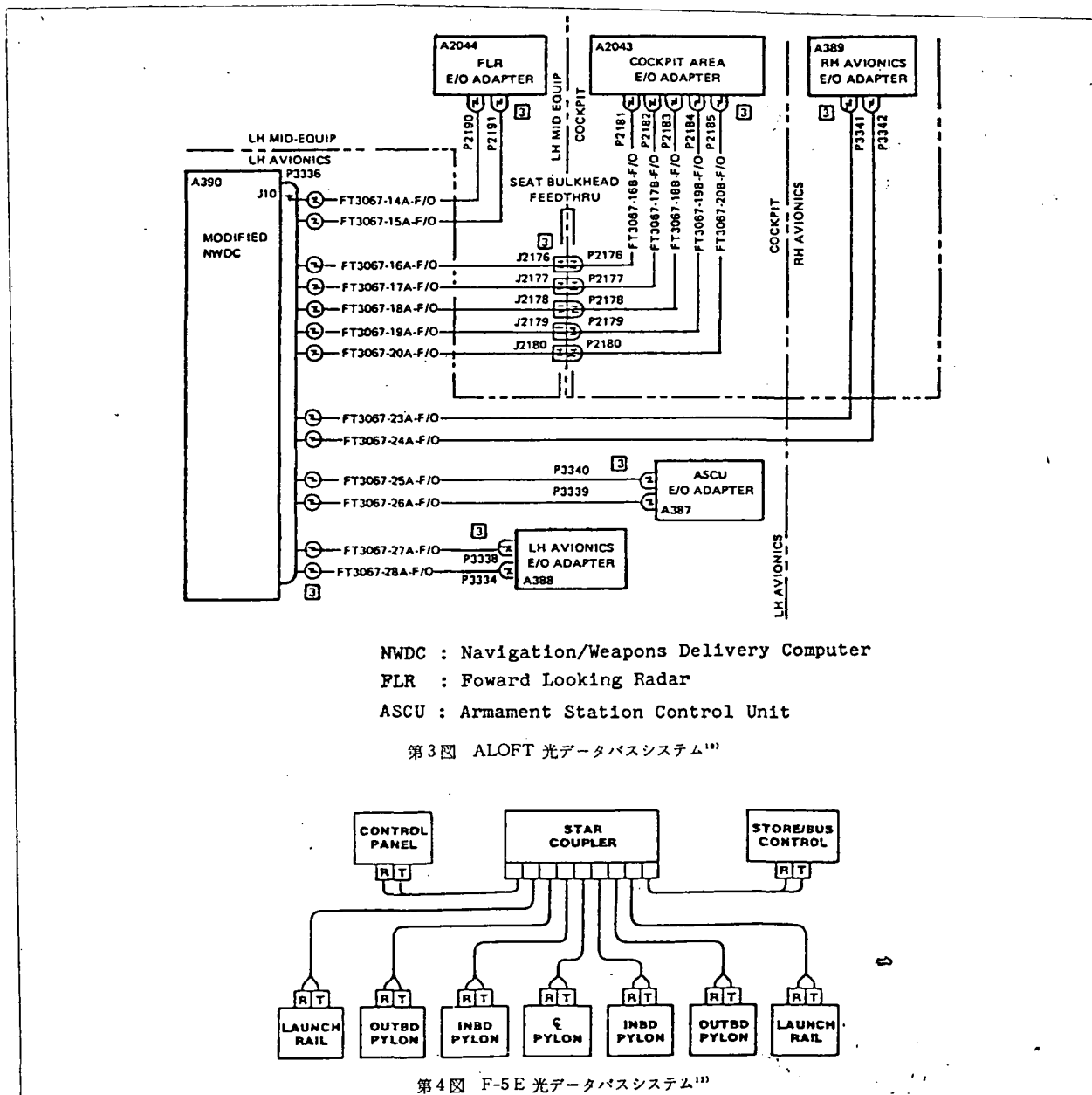
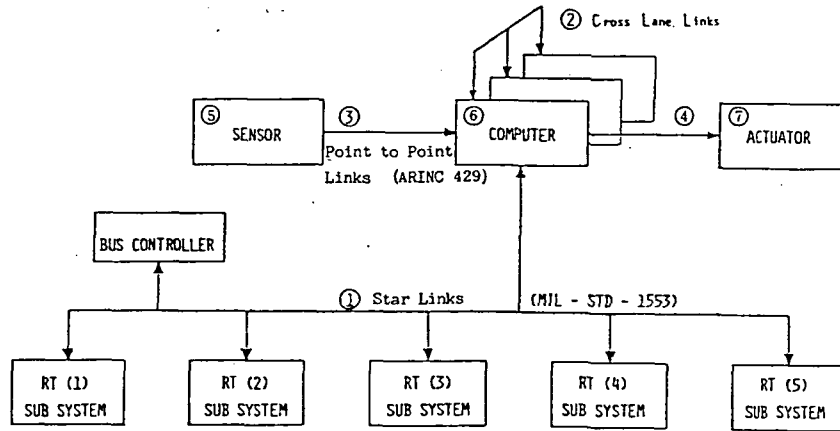
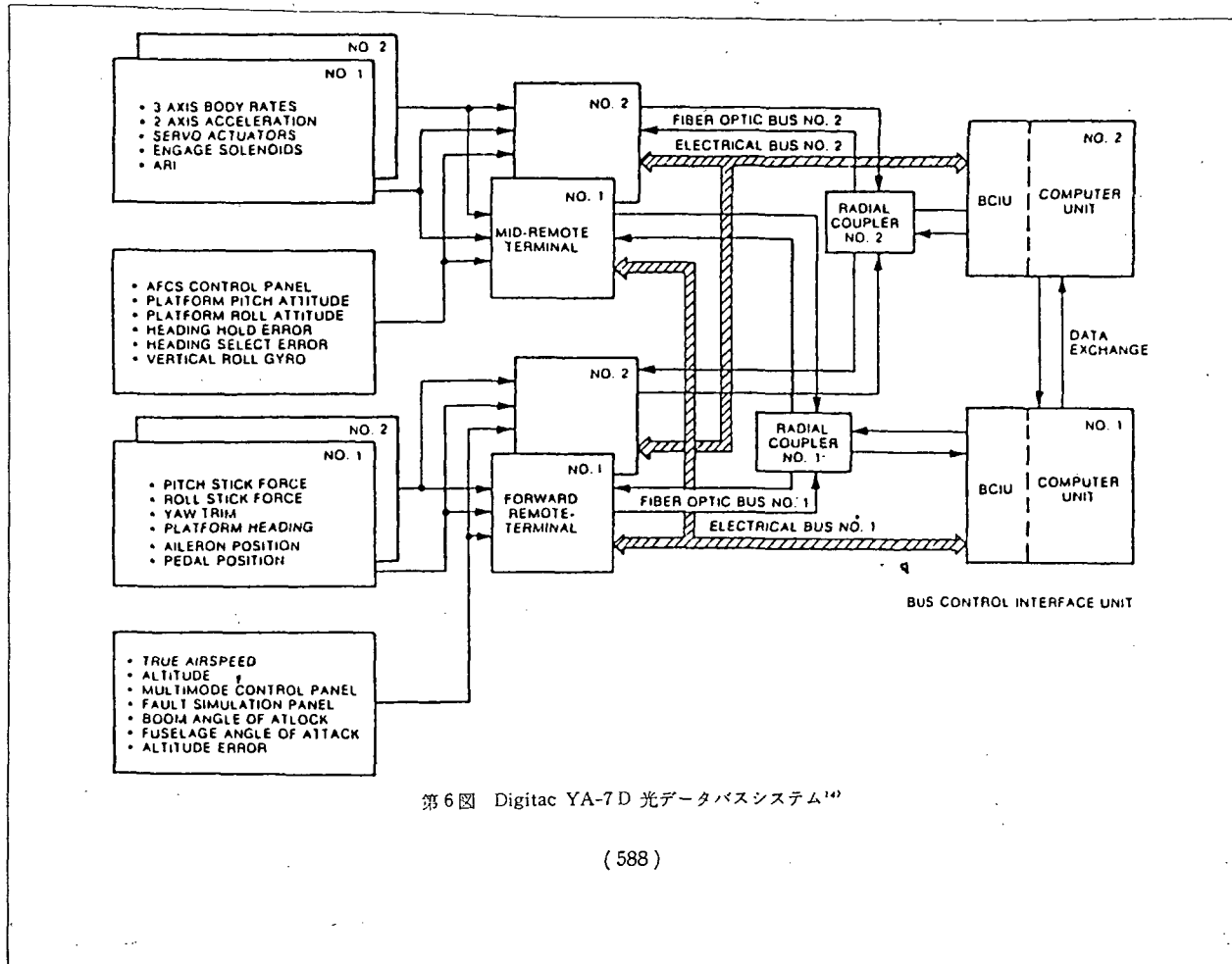


Fig. 2



第2図 飛行制御システムの光ファイバーリンク形態⁴⁾

Fig. 6

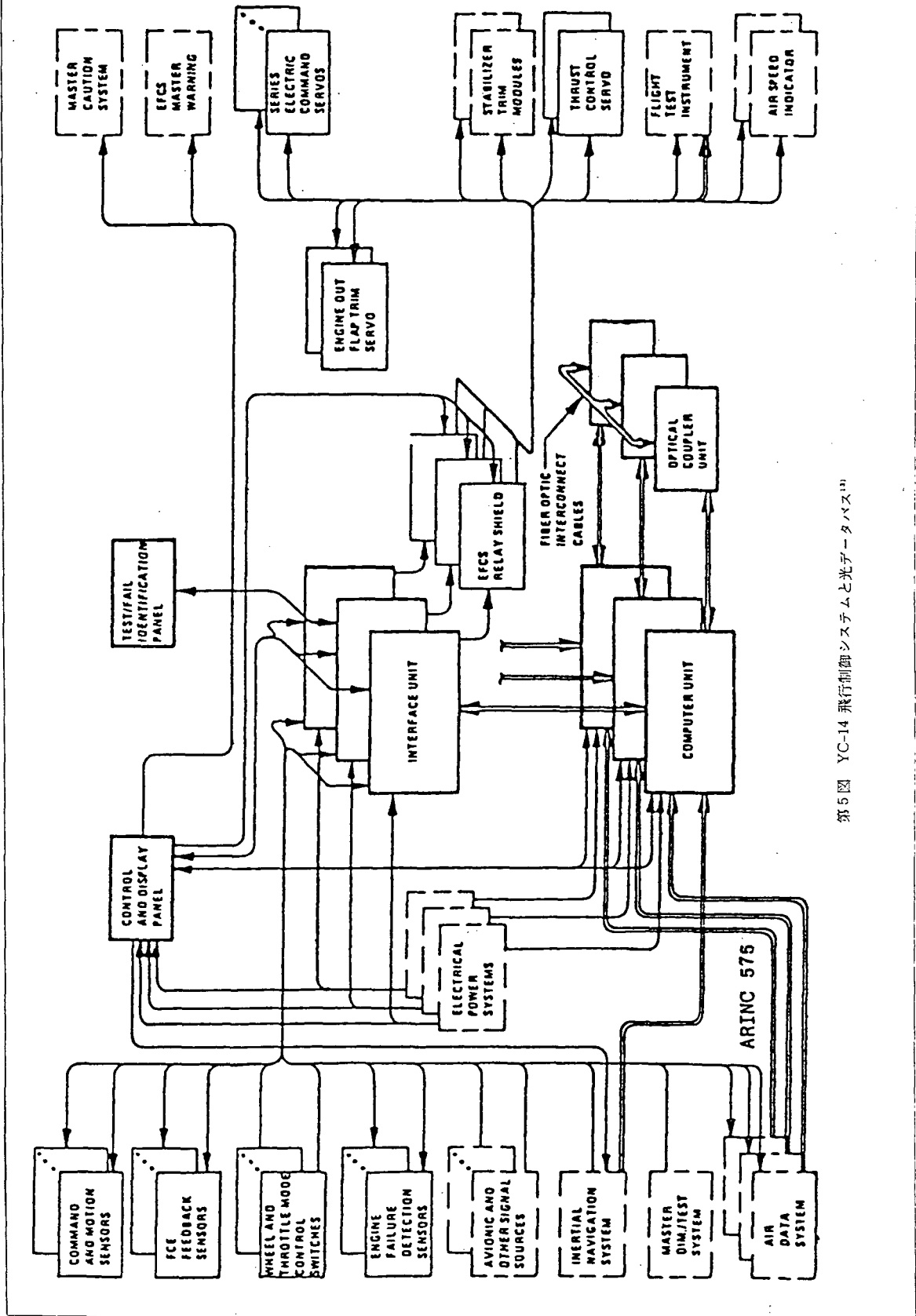


第6図 Digitac YA-7D 光データバスシステム⁴⁾

Fig. 5

飛行制御システム用光技術 (真柳光美)

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第5図 YC-14 飛行制御システムと光データバス¹⁾