Mechanical Engineering Technical Memorandum 150

TESTS IN THE DEVELOPMENT OF A CRASH RECORDER

by D.R. Warren

April 1958
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<table>
<thead>
<tr>
<th>CONTENTS</th>
<th>Page No</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. PROPOSED CRASH RECORDER</td>
<td>3</td>
</tr>
<tr>
<td>2. THE MICROPHONE PROBLEM</td>
<td>3</td>
</tr>
<tr>
<td>3. PRELIMINARY TESTS AND MEANS OF IMPROVEMENT</td>
<td>4</td>
</tr>
<tr>
<td>4. THE MINIFON TYPE 34 RECORDER</td>
<td>4</td>
</tr>
<tr>
<td>5. CHOICE OF FREQUENCY RANGE</td>
<td>5</td>
</tr>
<tr>
<td>6. MICROPHONES AND DIRECTIONALIZING METHODS</td>
<td>5</td>
</tr>
<tr>
<td>7. FLIGHT TESTS</td>
<td>7</td>
</tr>
<tr>
<td>8. CONCLUSIONS</td>
<td>8</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>8</td>
</tr>
<tr>
<td>APPENDIX A. : Other developments since 1954</td>
<td>9</td>
</tr>
<tr>
<td>APPENDIX B. : Design considerations</td>
<td>10</td>
</tr>
<tr>
<td>APPENDIX C. : Specifications No. I</td>
<td>12</td>
</tr>
</tbody>
</table>
In developing an accident-investigation device, tests have been carried out to determine whether inter-
pilot conversation can be continuously recorded with
small unobtrusive microphones mounted on the dashboard
or control column. By accentuating directionality and
limiting background noise with appropriate filters it
has been possible to obtain 96-100% intelligibility in
the Viscount and 80-94% in the DC6B. The method is
not practical in older non-pressurized aircraft where
cockpit sound levels are 10-25 db higher in the speech-
frequency range, but available evidence suggests that
even clearer records should be obtained in more recent
aircraft such as the Comet and Britannia.

Major factors affecting the design of such a
recorder are considered, and specifications for a
prototype are drawn up.
1. **PROPOSED CRASH RECORDER**

With the current trends to higher speeds, greater altitudes and longer flight stages over oceans and polar regions, an increasing proportion of aircraft crashes now occur without crew survival, without witnesses on the ground and with only mutilated debris for evidence. The need for ascertaining the causes of these accidents accurately is imperative as ever, especially when they may pinpoint intrinsic weaknesses in new types of aircraft.

At the time of the Comet disasters, which will illustrate this fact, an idea was put forward for assisting in the investigation of such accidents Ref. 1. It was suggested that aircraft should be equipped with a miniature continuous-loop wire recorder with sufficient memory time to retain any relevant pilot conversation immediately prior to the crash. To avoid fire damage it was suggested that the wire should be automatically ejected clear of the wreckage. It would also be possible for essential flight data to be coded onto the wire without interfering with the speech record.

The present memorandum outlines a number of tests carried out to assess the feasibility of such a device and to enable a prototype to be constructed.

2. **THE MICROPHONE PROBLEM**

Because of the high noise level in airline cockpits it has usually been found necessary, both for radio telephony and for internal public address systems, to use a noise-cancelling microphone held close to the pilot's lips. Alternatively, in military aircraft, throat microphones are used.

For the present purpose neither of these alternatives is suitable. A head microphone will not be picked up in an emergency. The continual wearing of throat microphones would not be acceptable to commercial airline pilots. Any suspension of the microphone on a stalk in front of the face would interfere with vision or movement.

The ideal solution would be a small microphone fixed unobtrusively to the instrument panel, control column or side of cockpit. Cockpit layouts for two typical modern aircraft (the Dornier and the Viscount) are shown in Figs. 1 and 2. While there are a number of possible positions for microphone placement, it is clear that distances of about 16 inches from the mouth are the closest one can achieve without inter-
ference. (Wall mounting is slightly closer but out of the line of speech).

A number of airborne trials were therefore carried out to see whether a sufficient degree of intelligibility could be achieved with such a microphone.

3. **PRELIMINARY TESTS AND MEANS OF IMPROVEMENT**

The first tests were carried out with a Minifon Type 54 wire recorder in the cockpit of a DC3. As could be expected, throat microphones gave records of typical "intercom" quality. But with the normal Minifon microphone (crystal, omnidirectional, high sensitivity) the speech record was badly distorted and drowned by background noise at speaking distances beyond 6 inches. Reducing the gain control two notch positions below the recommended setting gave only a slight reduction in the distortion.

Three ways of improving this result were recognised:

(a) The microphone-recorder combination had been designed for normal conversation. Under the high noise field of the plane either the microphone or amplifier could be overloaded or the saturation point of the wire exceeded. A rematching of components was therefore necessary to eliminate the distortion.

(b) Engine noise covers a much wider frequency range than does human speech. Much improvement could therefore be expected by using an appropriate band-pass filter.

(c) As the position in space of each pilot's mouth alters very little during flight an accentuation of microphone directivity should increase the ratio of speech to reverberated noise.

4. **THE MINIFON TYPE 54 RECORDER**

As no technical data on the instrument was readily available, it was dismantled and tested to find its characteristics.

It consists of a 3-valve amplifier (Fig. 3) with a potentiometer in the grid circuit of the final stage to control both recording gain and playback volume. It has a high impedance input shunted with a 5 megohm resistance.

It was found that on the recommended gain setting the amplifier would accept an input signal at 1000 c.p.s. of up to 5 mV without serious distortion.

The effects of the gain control for various input voltages
were measured (Figs 4, 5). These show that advancing the gain control can give full compensation for inputs down to 1 mV while any greater than 10 mV will be badly distorted whatever the gain setting.

By running the recorder with and without wire, with and without the governor operating, etc., the various sources of background noise were determined as shown in Fig. 6. Most was found to come from governor sparking. Changing the capacitance across the points or providing more shielding round the first amplifier stage did not reduce the noise. However, it was observed to increase each time the head cleared the bottom of its traverse and was apparently being picked up in the head itself. This will be kept in mind for avoidance when designing the prototype recorder.

The overall response curve of the recorder between recording input and playback output for a 5 mV signal is shown in Fig. 7. The governors speed of the wire in this case was 9 inches/second.

5. Choice of Frequency Range

Engine noise in an aircraft cockpit covers a very wide frequency range, the spectrum depending mainly upon the type of engine and the degree of acoustic insulation offered by the fuselage. The latter attenuates higher frequencies more than low.

In Figs. 8 and 12 are shown the sound spectra in the cockpits of a number of aircraft. Also shown in the spectrum for raised human speech, which is seen to cover a much more limited field. In choosing the frequency range of noise filters, however, another feature must be considered. Although most of the energy of speech lies in the 300-1000 c.p.s. range, the intelligibility is much more dependent upon the higher frequencies. In Fig. 9 (taken from Ref. 2) the effects of low- and high-cut filters on both the total energy and the degree of intelligibility is shown. With this in mind a band pass of 600-2500 c.p.s. was chosen for the first tests.

6. Microphones and Directionalizing Methods

It was decided to use low-impedance microphones because of the need for long leads to the recorder. To match these to the Minicon a small pre-amplifier was constructed (Fig. 10) which acted as the band-pass filter, having a 6 dB/octave cut below 600 c.p.s. and a 9 dB/octave cut above 2,500 c.p.s. A switch enabled the high cut to be eliminated for increasing articulation if found necessary.
The ideal microphone for the present purpose would be small and extremely directional, preferably picking up only in a cone of a few degrees. Such a microphone does not exist, but there are a number of ways in which some directionality can be achieved.

(a) **Velocity Microphones.**

These are intrinsically directional because of their dependence upon the velocity rather than the pressure of the air molecules. Three types were available for test. The Zephyr Hi-Fi Ribbon Microphone has a flat frequency response and a figure-eight directional pattern (Fig. 11a). The Philips Elipsoid has a hypercardioid pattern as in Fig. 11b. The Lustraphone noise-cancelling microphone is designed for use close to the lips, but can be used at greater distances with extra amplification. It has a marked resonance at 1600 c.p.s. and clarity was found to be very poor. Its directional pattern is similar to the Elipsoid (Fig. 11b). With all these microphones the sensitivity gain for "front-on" noise over random noise is about 5 db.

(b) **Acoustic Phasing.**

If sound waves can reach a microphone by two or more paths, then path lengths can be adjusted so that sounds from any one point will always arrive in phase. From any other point they will at least be partially self-cancelling.

This principle was applied in two ways. Firstly, a piece of plywood one foot square was taken to represent part of the instrument panel. Through it were drilled seven holes at convenient points and these were connected to a small pressure microphone by rubber tubes of such length that the total path length from a point 16 inches in front of the board (the pilot's mouth) was constant. This was referred to as the "Dashboard microphone". Its directionality was tested and gave the expected pattern shown in Fig. 11c.

The second method was to construct a small "machine-gun" microphone, consisting of a bundle of seven ½ inch bore copper tubes varying in length from 1 to 13 inches by 2 inch intervals (See Ref. 3 page 25a). These were attached to a microphone capsule so that any sound coming in the direction in which the bundle was aimed would arrive via each tube in phase. Any sound from the side would have a path-length difference of 2 inches for each tube. This was expected to give a very pronounced directional effect (See Ref. 3). However results in the air were found to be so poor that it was tested in an anechoic chamber and found to have the directional pattern shown in Fig. 11d. Even
though loss tubes were used, there seemed to be no immediate explanation why the peak sensitivity should be at 30° on either side instead of on the axis.

Many other methods of accounting directionality were considered. These included horns, parabolic reflectors and zone plates but all suffered from the same defect — their dimensions had to be at least of the order of the wavelength of the sound concerned (1 ft. for 1000 c.p.s.). The "dashboard" microphone seemed to be the only way in which sound pick-up points could be spread over these distances and yet be sufficiently unobtrusive in practice.

7. FLIGHT TESTS

The microphones were tested under cruising conditions in both the Viscount and DOG9 cockpits where overall sound-pressure levels were 95 and 96 db respectively. To avoid interference with the pilots, tests were made with the microphones at position A (Figs. 1 and 2) and the mouth 16 inches away. The microphones were fed to the combined preamplifier and filter then through an attenuator to reduce the peaks to 5 mV for the Minifon.

As part of the test on each microphone a piece of prose (about 100 words) was dictated. Later, in the laboratory, an assistant endeavoured to rewrite this from the wire record. The percentage word return afforded at least an approximate intelligibility index by which the microphones could be compared. The results were as follows:

<table>
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<th>Microphone</th>
<th>DOG9 (%)</th>
<th>Viscount (%)</th>
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<tbody>
<tr>
<td>Zephyr speech insert</td>
<td>77</td>
<td>77</td>
</tr>
<tr>
<td>Luxophone</td>
<td>69</td>
<td></td>
</tr>
<tr>
<td>Zephyr Ribbon</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>Phillips Ellipsoidal</td>
<td>96</td>
<td>96</td>
</tr>
<tr>
<td>&quot;Dashboard&quot;</td>
<td>94</td>
<td>100</td>
</tr>
<tr>
<td>&quot;Machine-gun&quot;</td>
<td>4</td>
<td>90</td>
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The "speech insert" was a completely non-directional microphone capsule. The poor results with the Luxophone are attributed to the pronounced ringing effect, due to 1600 c.p.s. resonance. (The unit may have been defective). Failure of the machine-gun microphone was due to its unexpected directional pattern (Fig. 11 d) whereby its main pickup lobes were directed outwards towards the engines with
a sensitivity 30 dB greater than in the direction of the voice.

Analysis of speech records made in flight revealed a considerable amount of pickup outside the chosen frequency range. It is therefore recommended that the low-frequency cut in particular should be made steeper than the present one of 12 dB/octave which arises from the combined action of the preamplifier and Minifon. As the noise (particularly around 100 c.p.s.) was much greater than that expected to pass the filter it may have come from microphone effects due to vibration of the recorder. This must be guarded against in future tests.

8. CONCLUSIONS

The suggested use of fixed unobtrusive microphones for recording inter-pilot speech appears to be a feasible proposition in modern pressurised aircraft. The method would have serious limitations, however, in most military aircraft or in earlier commercial airlines where sound levels are some 10–25 dB higher in the speech-frequency range.

With the current swing to turboprop and pure-jet engines, and with improvements in engine silencing and acoustic insulation, future aircraft should present very little problem at all. This is illustrated in Fig. 12 by the noise spectrum inside the Comet (from Ref. 4) and an estimate of that inside the Britannia (taken from a comparison of Vickers and Britannia noise by R.V. Pavia).

Much would be gained in both the present problem and in other problems involving high background noise levels by the development of small, highly directional microphones such as the "dashboard" one tested.

9. ACKNOWLEDGEMENTS

The pre-amplifier and filter unit was designed and constructed by G. Cadman of Instruments Group. Frequency analyses were carried out by E. Marfield. Flight trials were kindly arranged by the Department of Civil Aviation. Microphone tests were carried out in the anechoic chamber of the Melbourne Technical College.
Since publication of the first memorandum on this device a number of alternative crash-recorders and similar devices have either been suggested in the literature or are being produced.

(1) The "Airrecord" (Ref. 6) is a fireproof camera taking photographs of the instrument panel at regular intervals throughout flight. Its main value would seem to be in test-flying rather than continuous commercial operation.

(2) The Gateway Crash Recorder (Ref. 7) uses a metal plate instead of wire and retains instrument data but not speech on a record-and-erase basis. Correspondence elicited no further details except that a prototype had been built, but demand did not justify production.

(3) The Ogil failure-sequence detector (Ref. 8) consists of a round rubber-studded hollow metal sphere to be ejected from an aircraft in the event of a crash. Inside are a series of tagged fuse-wires, each connected to a microswitch which would close on some specific failure of a component or structure. From the degree of scoring produced it would be possible to fix the sequence of failure.

(4) An unconfirmed report was published in the Australian press that the Civil Aviation Authority was fitting commercial airliners in the United States of America with a crash recorder for retaining flight data in accidents. Enquiries on our behalf by Department of Civil Aviation have so far produced no further details.

(5) Headquarters Air Rescue Service in the U.S.A. has produced a Crash Locator System for installation in Air Force Aircraft (Ref. 9). It consists of a radio beacon weighing 4.5 lb. which is automatically catapulted from the crashing aircraft, parachutes to the ground, erects itself on legs or floats if on water and emits a distress signal to which a network of ground direction-finding stations automatically lock-on.

(6) The National Aeronautical Establishment of Canada are developing a "Crash Position Indicator" along the same lines as the previous device. Their beacon is a package about 5 inches thick and 2 feet square, weighing 12 lb.

While the purpose of the last two devices are crash location and not data-preservation, it is fairly clear that the two functions could be combined so that only one ejection mechanism would be required.
Among the compromises to be made in designing a recorder are the following:

1. What length should the "memory" be?
   The original suggestion of, say, 2 - 5 minutes would reduce any objection by the pilot to having an "all-hearing ear" which might be played back at the end of the flight. All record of the flight would be erased during taxi-in. However the value of the device would be greatly increased by extending the memory to, say, 3 hours or whatever might be full time of the flight. The extra weight of wire or mechanism would be negligible. As the question of pilot attitude has yet to be considered it was decided to make the prototype with a memory of 3 minutes to 3 hours, variable at will.

2. Should the instrument be ejected on crashing?
   Ejection may save the record in the event of a fire or a crash in deep water, but on the other hand it may also cause loss of the record in some cases where the main wreckage is found. If retained in the aircraft, a study of crashes in which fire has occurred suggests that the tail unit is the safest place for retention. This section often breaks off and falls clear, or at least does not suffer the intense heat which can completely destroy the centre and forward parts of the aircraft. It was therefore decided to rely on the fact that the stainless steel wire retains its magnetic image to a temperature of more than 500°C and plan the prototype for retention in the aircraft tail or rear pressurised fuselage.

3. Should flight data from instruments be included in the records?
   While in some cases the speech record alone might be of value, there are others in which only instruments could reveal the whole story (e.g. Comet explosions). To add instrument data means a considerable weight and cost penalty mainly due to the transducers rather than to the electronics required. It was therefore decided to include the necessary electronics in the recorder and thus allow transducers to be added (up to eight channels) as the occasion justifies.

4. Should there be self-contained batteries?
   Connection to the main supply will usually enable the recorder to run until the moment of impact, possibly longer. But there are cases...
(e.g., power supply short-circuit, broken propeller severing power lines) in which the prime cause of the accident would itself stop the recording. It would therefore be advisable to include batteries sufficient for at least a few minutes run-on in the event of power failure (e.g., 5 hearing-aid cells type H13 in parallel were found by test to provide the necessary 2 watts for about 12 minutes before dropping to 20 volts.

(5) What would be the most reliable "memory" mechanism?

A single continuous loop of wire would involve no reversing and no gaps in the record, but would only be feasible for a short memory (e.g., 2 minutes) on account of the length involved. A "continuous cassette" was likewise considered impractical. Recording on a drum of metal with a flip-back record/erase head would be feasible but very prone to loss by distortion in a crash. The use of two wires was finally chosen, one wire being erased and used for recording while the other containing the stored record is being run back.

The chosen method of doing this is to have four spools, one pair rotating together on one shaft and the other pair contra-rotating on a second shaft. With the wires connected as in Fig. 13 one of the latter pair of spools (A) is used to drive the system while its contra-rotating partner provides the drag to keep the wire taut. Reversal is affected by changing the drive from one of these spools to the other. Methods considered for doing this include spring-belt change-over between two pulleys (relying on belt slip to reduce snatch), use of two motors (one on each spool), and, thirdly, a two-sided magnetic clutch between the spools. Of these the latter was chosen, as its inertia loading was such that it would give considerable fly-wheel effect yet a minimum of snatch on changeover. Moreover it can be operated by a simple end-of-wire trip switch. At the same time precautions may have to be taken to prevent interference by inductance between the clutch and the recording head.
Appendix C
Specifications Mr. I

Wire Deck

The wire-deck and associated mechanism is to be similar in size, weight and function to the Minifon recorder but with the following exceptions:

1. The unit is to record continuously and automatically. Occasional gaps in the record of not more than a few seconds would be tolerated.
2. The record is to be automatically erased after a pre-selected period of time which may be between 3 minutes and 3 hours.
3. The unit is to be completely automatic from switch-on to switch-off.
4. Maintenance should not normally be required under 1000 hour.
5. Failure rate during this period from any cause should not exceed 5%.
6. The unit is to operate from 24 - 28 volts D.C.
7. Playback and rewind facilities are not required.
8. Wow should not exceed 2%.
9. Wire speed should be 2 - 12 inches/second.
10. Incorporated in the mechanism there is to be an 8-pole commutator-type switch cycling at 15 - 30 cycles per minute.

Electronics

1. The speech amplifier is to accept the output of a 50/3
dynamic microphone (such as the Philips Ellipsoid) accepting male raised
voice at 18" with engine noise, back-ground of 95 db. The amplifier is
to impose a basic cut of not less than 12 db/octave below 600 c.p.s.
and a trouble cut (9 -12 db/octave) above 5000 c.p.s..
2. The instrument-data channel is to accept signals from up
to 8 strain-gauge transducers (output 0 - 10 µA) via the 8-pole
commutator switch at about 2 - 4 seconds per cycle. These are to be
converted to an appropriate form (either A.M. or P.M.) for recording in
the 100 - 400 c.p.s. range or in the 4000 - 7000 c.p.s. range.
3. The combined output of both channels (Max. 5 volts) is to
be fed to a Minifon Type 55 recording head.
4. Operating supply is to be 24 - 28 volts D.C.
5. A trial mock-up is to be built (any size) and fitted with
an attenuator for varying input to find optimum for a given micro-
phone position and background. Optional automatic volume control and 12 db speech clipping are to be included for checking possible benefits in actual flight.

(6) Final version incorporating factors chosen in (5) above, is to be miniturised and built into space around wire-deck.

Case and accessories

(1) The case is to be of metal and hermetically sealed to retain one atmosphere pressure when at altitude, unless it is intended for placement inside the pressurised section of the aircraft.

(2) It is to be of minimum size able to contain:

(a) The wire deck
(b) The amplifier
(c) A 24 volt dry cell of sufficient capacity to run the recorder for 5 - 30 minutes.
(d) A male 16 pin plug to the outside.
(e) A relay to switch to batteries if power supply fails before scheduled switch-off.
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Printed by 2014 September 23 17 20
FIG. 1 VISCONT COCKPIT LAYOUT

FIG. 2 DC-6B COCKPIT LAYOUT
FIG. 4 PERMISSIBLE INPUT SIGNAL STRENGTH FOR VARIOUS GAIN SETTINGS

FIG. 5 EFFECT OF INPUT GAIN CONTROL ON RECORDED SIGNAL
SOURCES OF BACKGROUND NOISE AND EFFECTS OF VOLUME CONTROL

Output (dB with regard to max. output at inc.)

Volume Control Position (Notches)

- Wire with max. signal (1000 C.P.S.)
- Erased wire running
- Governor sparking
- Motor brushes
- Amplifier hiss (motor off)
Dynamic microphone pre-amplifier and speech-band filter
DIRECTIVITY PATTERNS FOR VARIOUS MICROPHONE SYSTEMS (AT 1KHz)

(a) RIBBON
(b) ELLIPSOID & LUSTRAPHONE
(c) "DASHBOARD"
(7 INLETS OVER 1 SQ. FT.)
(d) "MACHINE-GUN" \((x = 1)\)
--- 50 TUBES (BERANER)
--- 7 * (THIS TEST)
SUGGESTED MEMORY MECHANISM AND GENERAL INSTRUMENT LAYOUT