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'SAFE OR NOT?' A PROACTIVE APPROACH TO LOOK AFTER AN AIRCRAFT DISPLAY AT THE HONG KONG SCIENCE MUSEUM

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Abstract

Being the first aircraft of Cathay Pacific Airways in Hong Kong, DC-3 *Betsy* has been displayed in its current suspended position at the Hong Kong Science Museum since 1991. The structural integrity of this historical aircraft as a composite object and the associated suspension system in relation to public safety have always posed significant challenges to conservators, amongst other conservation concerns, and would often impose complications on conservation decisions. In those days when the methodology for structural evaluation of its suspension gears was yet to be established, the Museum would replace the gears twice a year to guarantee the system was in functional order and in compliance with the local safety regulations. To facilitate the work, part of the exhibition hall had to be temporarily closed for public safety during the work period and hence the visitors had to detour accordingly. Though this practice could fulfil the local legislative requirements, it was not cost-effective to take care of the display in this fashion, especially because the replaced devices might still be in good condition for future use. Whilst every care had been focused on the suspension gears, no technical information indicating the structural stability of *Betsy* was ever available and therefore the safety of the overall display was almost unknown to the conservators. With the support from local expertise, a structural health monitoring (SHM) programme has been devised for monitoring the suspension gears of *Betsy* so as to evaluate their structural performance. Through a continuous monitoring process, with technical analysis on the data collected, we are able to obtain a full picture on the performance of each part of the suspension system. Although *Betsy* has no further airworthiness consideration, we engaged aircraft engineers to devise an inspection programme with which the whole aircraft structure can be guaranteed in a 20-year cycle with zonal inspections to be conducted every 5 years. With the provision of these exercises, we are now able to provide a more cost-effective and practical way to continuously assess the stability of both the *Betsy* and its suspension system for permanent display, while minimising disturbance to visits as well as to the venue management of the Museum. This paper illustrates the process of devising a proactive approach to the caring of large technology artefact, in particular on the development process of the SHM system and the DC-3 Aircraft Maintenance Schedule (AMS) to determine the structural stability of *Betsy* and the associated suspending system. It not only depicts the advantages of the new and proactive approach over the old one, but also illustrates how the key features of the new approach are effectively and efficiently integrated into the long-term conservation strategies of the aircraft collection.

Keywords
DC-3 Betsy, suspension gears, structural health monitoring, strain, aircraft maintenance schedule, structural stability.

Research aims

- To identify the limitations and deficiencies of the original practice in looking after the DC-3 aircraft display at the Hong Kong Science Museum.
- To devise and implement a new approach to take care of the aircraft display more proactively and cost-effectively.

Introduction

The historical DC-3 Betsy

The golden age of aviation history in Hong Kong began with the establishment of the first commercial airline, Cathay Pacific Airways, after the Second World War. Flying as the first commercial flight of the Airways from Sydney to Shanghai via Hong Kong on 28 February 1946, DC-3 *Betsy* formed part of the backbone of the Airways' fleet in the early 20th century. However, with the tremendous development of the aircraft industry in subsequent years, larger-capacity piston-engined airliners and passenger jets became available, particularly the renowned Boeing 7-series; the iconic DC-3 *Betsy* then stepped down gradually from her career ladder and commenced the second stage of her life as part of the permanent collection of the Hong Kong Science Museum in 1989.

Manufactured by the former Douglas Aircraft Company, DC-3 *Betsy* is a twin-engine monoplane with hydraulically operated retractable landing gear under each nacelle and the empennage. With a wingspan of nearly 30 metres and a net weight around 7 tonnes, its fuselage is a semi-monocoque design consisting of transverse frames and longitudinal members covered with aluminium skins riveted to the frames and stringers (Federal Aviation Administration, 2012). As *Betsy* had been used as a cargo plane in the final years before her 'retirement', all passenger seating and related facilities had been dismantled and discarded.

Betsy as a displaying museum collection

It was a perfect moment for collecting *Betsy* in 1989 while the construction of the Hong Kong Science Museum was still in progress. Being the first aircraft collection in the local museums and given the historical and cultural merits attached to it, it was the decision of the Museum that *Betsy* should be displayed at a prominent location that would allow easy viewing by visitors from all sides yet sacrificing little space for the display of the object. The finally adopted suspension mode of display is in line with the concept as put forward by the Museums and Galleries Commission that suspending an aircraft in a typical in-flight attitude does add drama to the display (Ball, 1990).

The suspension methodology was developed with reference to the specifications of a DC-3 aircraft together with a series of critical engineering calculations, which came up with the following system:

- Three steel eye-rings were installed onto the structural members of the building as ceiling anchors to take the dead weight of *Betsy* and all dynamic loads imposed to the object from the environment;
- Structural fittings located at the nacelles and empennage, which were pre-designed to lift the aircraft for regular maintenance work in a hangar during her service life, were selected as the suspension points of *Betsy*. The attachment mechanism of each hoisting point was carefully designed to make sure that such suspension could be done on permanent basis without any damage to the aircraft structure (see Fig. 1).

Original approach in maintaining Betsy

Similar to the practices in many other countries, the use of lifting and hoisting appliances in Hong Kong is governed by statutory regulation. Regulation 18(1) of the Factories and Industrial Undertakings (F&IU) Regulation stipulates that: 'each chain, rope and lifting gear in use shall be thoroughly examined by a competent examiner in the preceding six months before it is used and a certificate in the approved form in which the competent examiner had made a statement to the effect that it is in safe working order had been obtained'. In those years when the methodology for in-situ structural evaluation of suspension gears was yet to be established, the only way to ensure their integrity was either through laboratory testing after detaching them from original positions or replacement with brand new, certified ones. As the former option would take about a couple of weeks to complete and the display would have to be closed for viewing during the period, the Museum had adopted the latter approach, following the installation of *Betsy* in 1989, to replace all suspension gears including sling wires and shackles twice a year to comply with the requirements of the corresponding F&IU regulation. For those ceiling anchors that could not be detached for separate testing, a Magnetic Particle Inspection technique (which is a non-destructive testing method for the detection of discontinuities on ferroelectric materials) was deployed for assessment of their structural integrity.

Figure 1: Suspending DC-3 Betsy from the ceiling of the Hong Kong Science Museum.

Though the replacement approach was apparently more favourable in terms of museum operation, the implementation of such an exercise was not as straightforward as one might have thought. Notwithstanding that a large-scale scaffolding platform was required to be constructed every time to provide workers full access to the suspension elements, there were certain inherent shortcomings in adopting such replacement approach, namely:

- There was no technical data on the structural condition of the suspension gears to justify the necessity of conducting the half-yearly replacement exercise;
- The costs for replacement of gears and construction of related supporting facilities are high;
- The replacement exercise would introduce additional stress to the aircraft structure particularly to those hoisting points during the dismantling and installation of sling wires;
- There was a high chance for the aircraft structure to get damaged due to the mishandling of tools when workers were working on the scaffolding platform;
- The exhibition hall underneath where *Betsy* was suspended had to be temporarily closed for 1-2 weeks during the replacement exercise;
- The practice did not cover the structural assessment of *Betsy* and therefore it was almost impossible to determine whether the aircraft was suffering from deterioration affecting her overall structural integrity.

In short, the considerable inherent shortcomings associated with the old approach necessitated that curators and conservators explored a more practical approach to safeguard the long-term interest of the unique, historical *Betsy*. As part of the developmental process to formulate a new approach, the following issues had been deliberated:

- Is there a more cost-effective way for looking after *Betsy*?
- Are there alternatives to minimise the replacement of suspension gears?
- How to justify the replacement of suspension gears?
- How to guarantee the structural integrity of *Betsy* for long-term public display?

A new and proactive approach

To resolve the above-mentioned issues we had initiated a cross-disciplinary study, with the professional input from various specialists including structural engineers, aircraft experts and curators, to review the long-adopted standing approach in order to manage *Betsy* as a permanent museum exhibit more proactively and systemically, with the following major objectives:

- To develop a non-destructive monitoring system continuously assessing the structural behaviour of all suspension gears;
- To carry out comprehensive checking of the aircraft to monitor and evaluate regularly its structural integrity for permanent exhibition;
- To enhance the overall safety of the display and to act in compliance with the local statutory requirements on a suspending display;
- To minimise the disturbance to public visits and museum operation.

Structural Health Monitoring (SHM) programme

The SHM technique has been widely developed in civil and structural engineering for continuous assessment of structural integrity and health condition of mega-structures like bridges, towers and high-rise buildings (Kiremidjian, et al., 1997). The fundamental concept of SHM is to collect structural data of the target structure through a well-defined sensor network. When any irregularities are detected in the data, further inspection and diagnosis of the structure is necessitated. Borrowing the experience of the SHM programme developed for the historical Fireboat *Alexander Grantham* (Tse et al., 2008), we collaborated with the SHM Division of the Hong Kong Polytechnic University (PolyU) to devise a health monitoring programme aimed at ensuring the proper functioning of all suspension gears for *Betsy*. The SHM Division of the PolyU has a very strong background in undertaking SHM projects to monitor the dynamic and static behaviour of high-rise buildings and mega-structures (Wong and Ni, 2009). The specific SHM programme consists of the following modules (Fig. 2):

- High-performance sensory system;
- Data transmission and acquisition system;
- Data visualisation, management and analysis system.

High-performance sensory system

Vibrating wire strand-meter

Eight sets of vibrating wire strand-meters were installed onto all of the sling wires suspending *Betsy* (Fig. 3). Any deformation on wire strands will affect the tension of the wire and the actual degree of change can be determined accurately by measuring the change of strain (see Fig. 4 for the locations of all the strand-meters (i.e. WL01-03, WR01-03 and WT01-02)).

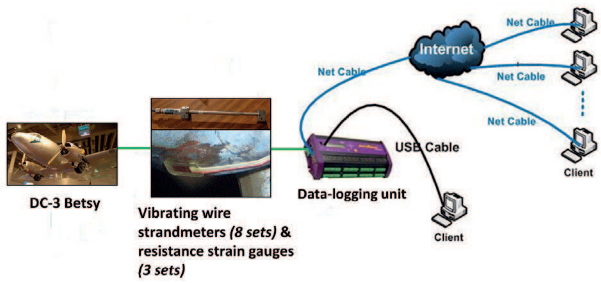

Figure 2: Schematic configuration of the SHM system for Betsy.

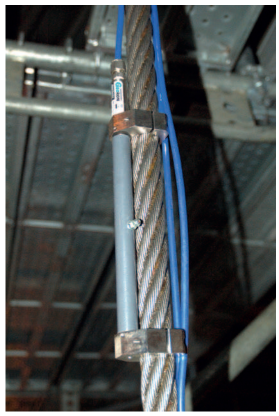

Figure 3: Vibrating wire strand-meter on sling wire.

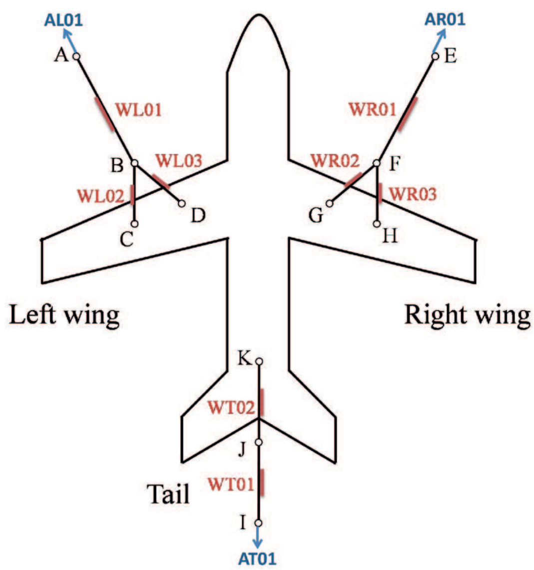

Figure 4: Location of all monitoring sensors for Betsy.

Resistance strain gauge

Three sets of resistance strain gauges were deployed for checking the integrity of the steel ceiling anchors (Fig. 5). Physical deformation of these structures can be determined through the change of electrical resistance detected by the sensors attached to the anchors. AL01, AR01 and AT01 in Fig. 6 represent the locations of the resistance strain gauges.

Data transmission and acquisition system

The data transmission and acquisition system consists of two major components; a cable network system for transmission of data and a data-logging unit to store all technical data acquired from the sensors.

Data visualisation, management and analysis system

A software system has been developed to facilitate the system configuration, data interpretation and analysis. An on-line data visualisation module has been devised so that the engineers, curators and conservators are able to observe the real-time performance of all sensors and examine if there is any anomaly in the readings. The data visualisation module is equipped with a user-friendly interactive interface showing the real-time data in the form of graphical plots. Users may alter the scale of the plotting by selecting the appropriate date and time, and even compare the data trends with other sensors in the same SHM system.

Figure 5: Resistance strain gauge, model FLA-3-11-3LT, on ceiling anchor.

Figure 6: A typical variation pattern between the temperature (in red) and strain readings (in green) of sensor WT02 (i.e. sling wire JK) between January and April 2013.

Two-level alarm strategy

As part of the SHM programme to detect any early signal of damage to or deterioration of the suspension gear, a two-level alarm strategy has been devised and adopted. The first level is an 'attention' signal while the second one is a 'critical' alarm. The attention level is triggered when the sling wire suffers a change of strain caused by 10% increase in loading applied, while the critical alarm will be set off when a 30% increase in the applied load is detected. To work out the reasonable level for each alarm signal, technical reports prepared by the surveyor who carried out the previous suspension gears replacement exercise were referred to in determining the estimated loading of each suspension component. The weight distribution pattern of *Betsy* as recorded in December 2010 is tabulated in Table 1.

While brand new sling wires were acquired (to replace the existing old sling wires) for suspending *Betsy* in order to dovetail with the implementation of the monitoring approach in January 2011, some of the sling wires from the same batch were taken to the PolyU laboratory to work out the actual relationship between change of strain and loading applied. During the test, the sling wires were first pre-loaded with loading indicated by the previous survey report as the baseline. The applied loading was then increased by 10% intervals to obtain the actual change of the strain value so as to work out the 'attention' and 'critical' levels for each sling wire. Final alarm levels adopted for individual sling wires are tabulated in Table 2.

Table 1. Weight information of sling wires suspending Betsy as recorded during the last replacement of suspension gears in January 2011.

Location of sling wire	Diameter	Estimated loading
AB (left wing)	28 mm	3,100 kg
EF (right wing)	28 mm	3,130 kg
BD / BC (left wing)	18 mm	2,000 kg / 1,100 kg
FG / FH (right wing)	18 mm	2,020 kg / 1,110 kg
IJ / JK (tail)	28 mm / 18 mm	730 kg / 730 kg

Table 2. Thresholds of the two-level alarm system for each sling wire

Sling wire	Attention Alarm (in micro-strain, µƐ)	Critical Alarm (in micro-strain, µƐ)
AB / EF	147	730
BC / FH	162	843
BD / FG	248	1307
IJ	40	203
JK	113	593

Preliminary results and findings

Over the last two years, since the commencement of the SHM programme in January 2011, it was observed that the strain readings would vary with temperature of the ambient environment giving rise to a temperature variation pattern (Fig. 6). Such patterns in fact follow the material properties such that, under a static mode of display with minimal dynamic loading introduced by the structure, strain reading decreases when temperature increases. In order to isolate those strain values responding to temperature variation, a data normalisation process was conducted so as to identify the change of strain due to the actual deformation of sling wires. Figure 7 illustrates the strain readings of sensor WT01 (i.e. sling wire IJ) before and after data normalisation.

Through the data obtained it is noticed that the strain performance of all sensors was maintained at almost the same level and hence we are able to draw a conclusion that the suspension system of DC-3 *Betsy* is extremely stable without any early signal of structural failure.

Though the SHM findings should be good enough to reflect the stable structural condition of the sling wires, in order to comply with the requirements of our F&IU regulation visual inspections to examine the physical form of the overall suspension system, including all cap bolts, high-tensile shackles and steel anchor plates, have also been conducted every six months since the commencement of the SHM programme. Through the site inspection, the engineer was able to obtain further information concerning the physical condition of all suspension elements so that he was fully confident to issue the safety certificates certifying their stable state as far as displaying a suspended object is concerned.

Additional care to Betsy

As part of the permanent museum collections on static display for more than two decades, *Betsy* had in fact no further airworthiness consideration, but her overall structural integrity is still of prime concern to the curators as far as public safety of a display object is concerned. With regards to this, a zonal inspection programme for *Betsy* has been established in collaboration with the Cathay Pacific engineers to condition-inspect the different zones of *Betsy* at regular intervals. In this exercise, the Cathay Pacific engineers have worked together with curators and conservators in developing an Aircraft Maintenance Schedule (AMS) for the decommissioned DC-3 based on Cathay Pacific's Boeing 747-400 AMS and the construction specifications of the DC-3. The DC-3-AMS is supplemented with a set of inspection work cards addressing the detailed procedure of each inspection task as well as the recommended frequency of every task.

Focusing on all structural members of *Betsy* including the landing gear, fuselage, nacelles and engines, stabilisers, wings and areas around the hoisting points, the first aircraft inspection was conducted in January 2011. Detailed visual inspections were performed on both the exterior and interior of the concerned areas by professional aircraft engineers, and all distortion, corrosion, damage and missing components were fully documented in the form of texts and images for follow-up action in the future.

As at January 2011, the overall structural condition of the *Betsy* was found to be satisfactory, except for some minor irregularities which necessitated conservation attention in the long run, namely:

- Slight metal corrosion (most likely oxides of aluminium) was noted under the floor panel of the main cargo compartment interior. After thorough inspection it was believed that the corrosion was due to water seepage through windows during its service life. After discussion with the aircraft engineers, corrosion was removed mechanically and at the next inspection a check will be made to see if the problem is getting worse;
- Slight corrosion was noted on the interior of the left wing. As the area was quite inaccessible, only photo-documentation was carried out and inspection on the concerned area will be carried out every 5 years to assess if there is any further development of the corrosion problem.

In the DC-3-AMS, Cathay Pacific engineers proposed the following checking cycle for *Betsy* so as to monitor her structural condition through a 20-year inspection programme:

2011 (Year 0)	Performed inspection on all locations on-board
2016 (Year 5)	To inspect the fuselage and all areas with corrosion noted in previous inspection
2021 (Year 10)	To inspect both wings and all areas with corrosion noted in previous inspection
2026 (Year 15)	To inspect the fuselage and all areas with corrosion noted in previous inspection
2031 (Year 20)	To perform inspection task on all areas again

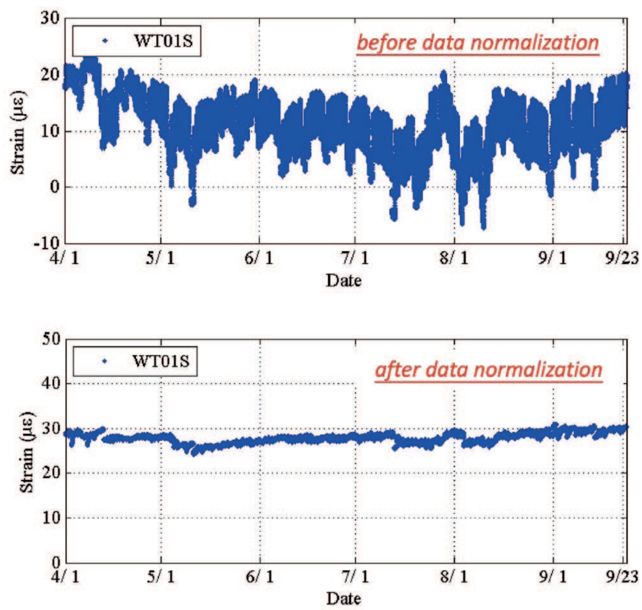

Figure 7: Strain readings of sensor WT01 (i.e. sling wire IJ) before and after data normalisation.

Bringing Betsy into a new era

With the implementation of the proactive approach in January 2011, we are now able to reap the benefits arising from the change.

Enhancement of overall safety

The old practice only focused on the integrity of suspension gear, but it could not provide any technical information regarding any change in health condition of the gears. With the SHM exercise, continuous assessment of their structural integrity was being performed and we would now be notified immediately once any of the alarms is triggered. Apart from the SHM programme, the condition inspection programme of *Betsy* will also be scheduled and conducted by professional aircraft engineers to critically evaluate her structural condition. As such, the overall safety standard of the display has been significantly enhanced.

No disturbance to public visits

In the past when the replacement of the suspension gears every six months was in place, part of the exhibition hall of the Science Museum had to be closed for 1-2 weeks to facilitate the work process. With the structural data continuously obtained through the new practice, no replacement of the suspension gears has been required for the past two years and therefore public visits to the corresponding exhibition area were not affected.

More cost-effective

Whilst almost HK$600,000 (~ £50,000) was required every year in the past for replacing all of *Betsy’s* suspension gears, only HK$300,000 (~ £25,000) a year is needed nowadays for the maintenance of hardware and sensors, data retrieval and analysis, submission of technical reports and issuance of safety certificates to comply with all statutory requirements.

Conclusion

Maintenance of a historical aircraft for public display is in fact a complicated and costly exercise for conservators and curators. In the old days, although sufficient care had been taken to look after the gears suspending *Betsy*, we did not possess any knowledge to help in certifying the integrity of the aircraft and as a result the overall safety of the display was almost indeterminable. Since the commencement of the new practice in early 2011, professional engineers are now able to assess the structural condition of its suspension gears on a real-time basis. Moreover, with the support from Cathay Pacific Airways, condition inspection of *Betsy* is also carried out at regular intervals to guarantee her structural integrity. With the provision of these proactive measures, disturbance to both the aircraft structure as well as the museum operation can be avoided.

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Materials and equipment

Vibrating wire strandmeter (model: 4410)
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Tokyo 140-8560, Japan.
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