Design, test and evaluation of an actively stabilised drogue refuelling system

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ABSTRACT

A scale model of aerial refuelling drogue is built and tested to investigate active drogue stabilisation and control concepts. A set of aerodynamic control surfaces is implemented to a conventional, aerodynamically stabilised refuelling drogue. The control surfaces are designed to reduce the response of the drogue motion to atmospheric disturbance and tanker motion. This paper presents the details of design concept and experimental results based on wind-tunnel testing of a ⅓ scale model fabricated for this study. To investigate the proposed active control concept, a dynamic test rig is built for wind-tunnel experiment. The rig basically represents a hose-drogue system in terms of a 4 degree-of-freedom (DoF), single link pendulum model. System identification technique is used to obtain a drogue dynamic model, based on which a feedback control law is developed. Closed-loop dynamic testing is carried out to evaluate the effectiveness of the aerodynamic surface control module and feedback control law.

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NOMENCLATURE

a_y drogue acceleration (m/s^2)
G_{Cy} drogue motion transfer function
K_{Cy} feedback controller
σ_y control command (degree)

Subscripts

C cross configuration
P plus configuration
y Y-axis (Side direction)
z Z-axis (Vertical direction)

1.0 INTRODUCTION

Aerial refuelling drogues used in the current hose-drogue-probe aerial refuelling method are an aerodynamic device, which primarily generates drag force for a receiver aircraft to couple with the refuelling hose. In a steady free-stream condition, it is statically balanced in the longitudinal plane with aerodynamic drag, hose tension, and drogue weight. The drag force is produced by a drogue canopy, which lifts up and holds (or stabilises) the drogue into an almost horizontal position. However, the drogue is very susceptible in the presence of disturbances such as atmospheric turbulence and tanker motion, which are all unavoidable in normal refuelling operations. Due to lack of lateral force balance these disturbances cause the drogue to move randomly in the lateral plane, thus demanding high pilot workloads and significantly limiting the refuelling operations. To overcome this deficiency, an actively stabilised drogue refuelling system (ASDRS) is sought, that reduces drogue motion and maintains the drogue position relative to the tanker in the presence of the disturbances[(1)]. If successful, such a system will greatly benefit both manned and, especially, unmanned operations in the probe-drogue-hose aerial refuelling method.

Some conceptual ideas of controlling a refuelling drogue in flight are proposed: 1) passive stabilisation through a gyroscopic effect induced by a rotating mass coupled with an air turbine located in the drogue, or a combination of both passive and active methods including aerodynamic control surfaces[(2)], 2) an active control method via implementing thrusters energised by pressurised air[(3)], and 3) an active stabilisation and control method by the drogue canopy manipulation[(4)]. While all these concepts are feasible propositions, design details that quantify and verify the concepts in dynamic environment of the hose-drogue refuelling system are very limited to date. A recent study by Williamson *et al*[(5)] investigated canopy manipulation concept as a means of active drogue control; wind-tunnel tests were carried out to characterise the aerodynamics of a controllable drogue, and developed a simple pendulum model representing the hose-drogue dynamic motion with the controllable drogue aerodynamic. This model was then used for numerical simulation study, and studied Linear Quadratic Regulator (LQR) control method for active drogue control.

Ro *et al*[(6)] developed a hose-drogue dynamic model based on a finite-segment approach, where the hose is modeled as a series of ball-and-socket connected rigid links. The physical and aerodynamic characteristics of the hose links are lumped at the connecting joints, and the drogue is treated as a lumped mass connected to the end of the hose with its own aerodynamic properties as described in Ref. 7. The results from the numerical simulation study of the model for the F/A-18 tanker are in a good agreement with published flight test results by NASA[(8)] Ro *et al*[(9)] further extended the model to study the hose-drogue dynamic characteristics during coupling, and a linear model of the

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Figure 1. A ⅓ scale drogue model.

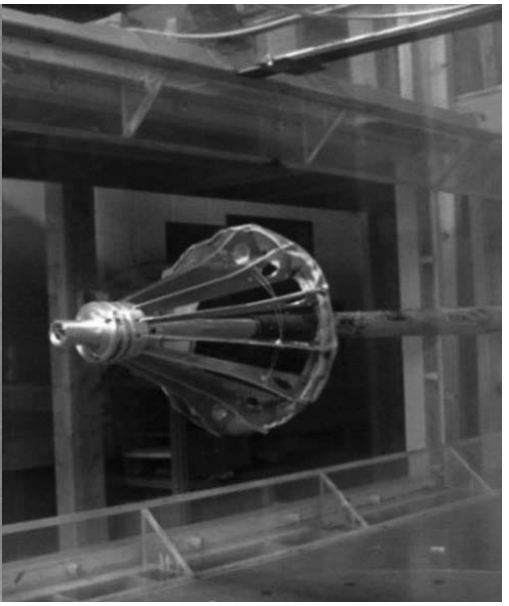


Figure 2. Static wind-tunnel test.

hose-drogue dynamic motion was obtained for ASDRS design study. A simple proportional-integral-derivative (PID) controller was designed, and implemented into the original nonlinear model to validate the design concept via a nonlinear, closed-loop simulation with atmospheric turbulence. The simulation results showed that the actively controlled drogue meets the desired specifications with the proposed control law. No design details or physical descriptions of actuation and sensing methods were studied, yet the required vertical and lateral actuation force of the ASDRS at a given flight condition were calculated based on the numerical simulation results.

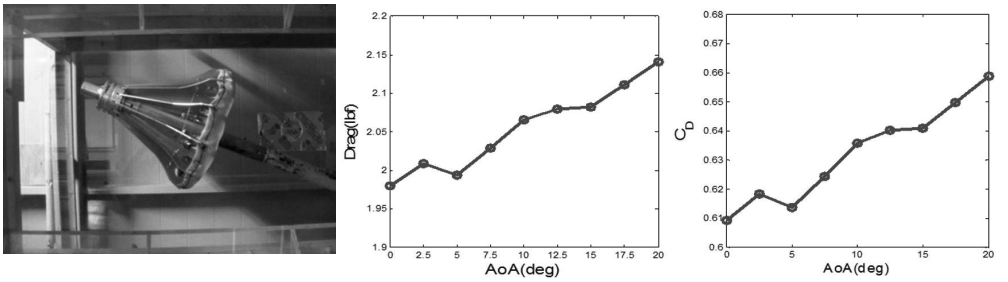
In this study, active control of a refuelling drogue is investigated by implementing a set of aerodynamic control surfaces to a conventional aerodynamically stabilised drogue. An 8in diameter, 12 collapsible struts weighing about 0·7lb, as shown in Fig. 1, is fabricated to test the proposed active control concept. This model is approximately ⅓ scale of a full size refuelling drogue. The scale factor chosen is to take into account dynamic testing in the Advanced Design Wind Tunnel (ADWT) at Western Michigan University, and also possibly a future study of conducting in-flight experiment on a scale model aircraft of a size similar to typical small unmanned aerial vehicles (UAVs), or a man-portable UAV, currently in use. A test rig is manufactured to carry out drogue dynamic testing in the wind tunnel. System identification technique is used to obtain a drogue dynamic model, based on which a feedback control law is developed. Closed-loop dynamic testing is carried out to evaluate the effectiveness of the aerodynamic surface and feedback control design.

2.0 DESIGN AND FABRICATION

2.1 ⅓ Scale drogue

A study on the aerodynamic characteristics of aerial refuelling drogue by Ro *et al*[2] reports that the drag force generated by a paradrogue depends on its certain geometric characteristics. The drag

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(a) drogue angle-of-attack (b) drag vs angle-of-attack (60mph) (c) drag coefficient vs angle-of-attack

Figure 3. Drag characteristics of the 1/3 scale drogue.

coefficient is determined through the design of experiment (DOE) technique using the wind-tunnel test data, which is a function of strut angle, chute area, and gore spacing. For this study, a nominal value of C_{drogue} = 0·8 is used for the initial baseline design of the ⅓ scale drogue model, which predicts approximately 2·6lb of drag force at 60mph, sea level condition; this condition represents a typical flight condition of a remote control aircraft to be used for this study. Static wind-tunnel tests are carried out as shown in Fig. 2, and the results are shown in Fig. 3. The static wind-tunnel test shows somewhat lesser drag value, which could be due to the drogue shut size used in the scaled model.

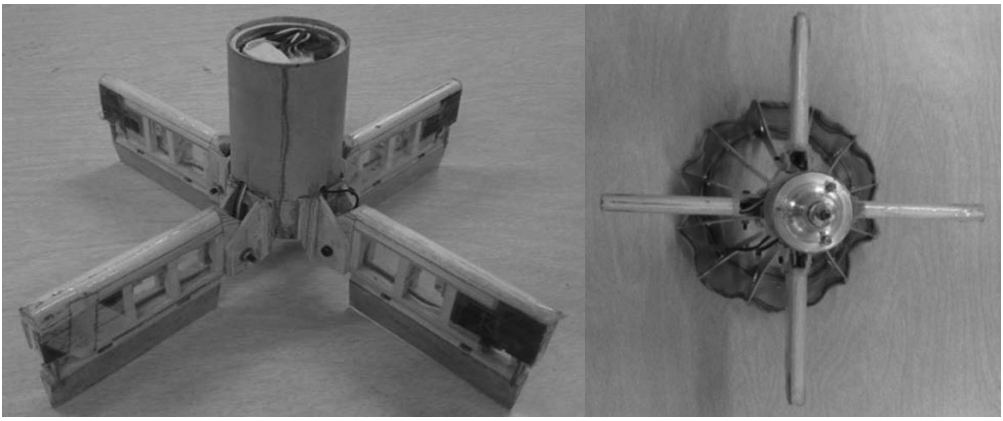
Assuming that a flight test model aircraft is equipped with a 5·2hp engine running at 7,000 rpm with a fixed pitch propeller of 22in diameter and 10in pitch, the available thrust from this propulsion system at 60mph is approximately 7~8lb[10]. By estimating some elementary flight performance calculations of the test model aircraft with a clean drag polar, the thrust required at this condition is about 2·08lb, thus should leave an adequate amount of excess thrust to pull the hose-drogue system.

2.1 Active drogue control actuator

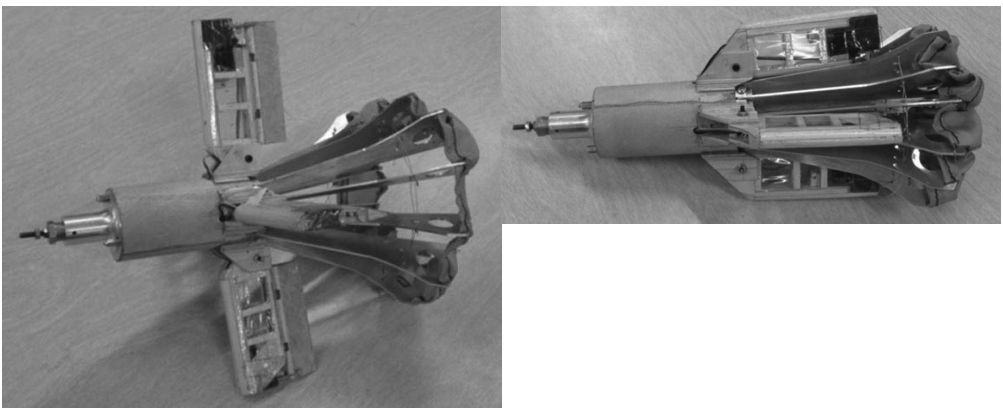
One of challenging design requirements for a possible actively stabilised drogue refuelling system (ASDRS) is that the design must easily adapt to the current hose-drogue aerial refuelling system (ARS) with minimal modification for drogue stowage and ARS exterior. In this study, a set of aerodynamic control surface is considered for a conventional aerodynamically stabilised drogue. The aerodynamic control surface module is designed to produce necessary amount of control forces to control the motion of the drogue in the lateral plane. A recent study by Ro *et al*[9] suggests that the longitudinal and the lateral motion of the drogue are decoupled from each other; thus a single-input-single-output (SISO) design for each channel would be a possible design choice. Thus, the control surface module should be coordinated to produce effective forces in the longitudinal and lateral direction. Given the requirements of easy adaptability and also minimal modifications to the existing probe-drogue-hose refuelling system, following design requirements for the aerodynamic control surface module are established: 1) it must be an integral part of an refuelling drogue for the maximum control authority, 2) it must be foldable to be stowed in ARS and deployed flawlessly when a hose-drum unit in ARS reels out the drogue, 3) it must be a stand-alone unit for its operations.

Figure 4 shows an aerodynamic control surface module implemented to the scaled drogue model. There are four aerodynamic surfaces made out of a NACA symmetric aerofoil section located external to the coupling portion of the drogue as shown in Fig. 4(a). Each surface has a

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(a) control surface module mounted coupling (b) controllable refuelling drogue



(c) deployed configuration (d) stowed configuration

Figure 4. Aerodynamic control surface configured aerial refuelling drogue.

trailing-edge flap which is connected to a servo housed inside the coupling section of the drogue assembly. This control surface module mounted coupling is connected to the paradrogue, as shown in Fig. 4(b), to generate required forces in horizontal and vertical direction. Each control surface is spring-loaded such that it can be folded when the drogue reels into ARS for stowage and deployed by a spring when the drogue reels out of ARS. Fig. 4(c) and Fig. 4(d) show deployed and stowed configuration, respectively. While the control surface size can be designed to generate a desired aerodynamic force, geometrical constraints are also an important factor for the implementation point of view. For this study, the control surface span is chosen to be 0·36ft and the chord length of 0·21ft to meet the geometrical constraints for easy stowage into ARS. The trailing-edge flap on each surface takes up 38·5% of the chord, and is linked to a servo actuator.

It is important to notice that the connection between actual hose and drogue coupling is a ball-joint configuration, and thereby the refuelling drogue is able to rotate relative to the hose approximately 22·5° in every direction[11]. This allows the refuelling drogue to sometimes rotate (mostly rolling due to pulling action by the drogue drag force) relative to the hose, in case there are some aerodynamic asymmetries on the drogue which causes enough aerodynamic force to

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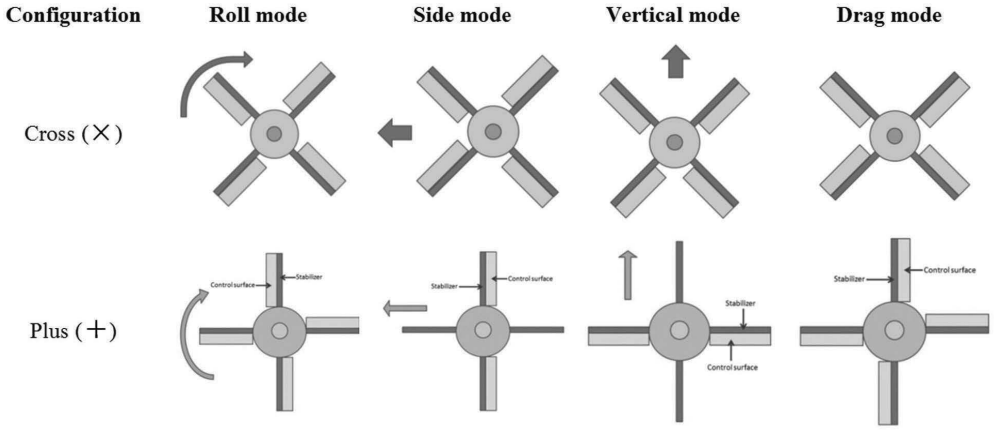


Figure 5. ASDRS control actuation mode.

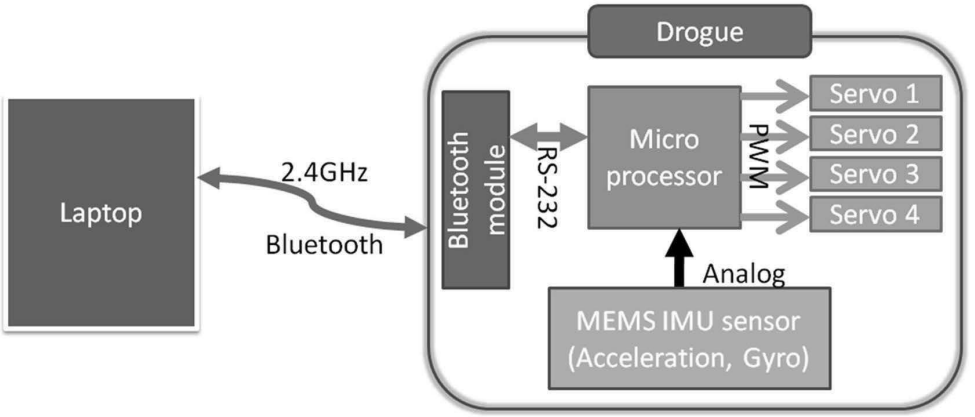


Figure 6. Onboard drogue control processor module.

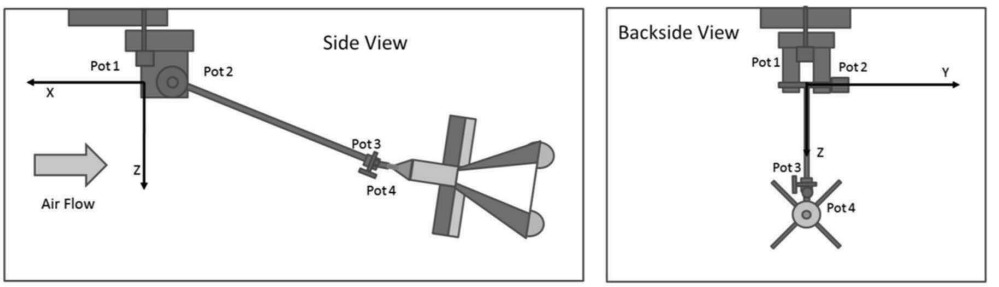


Figure 7. Dynamic test rigs.

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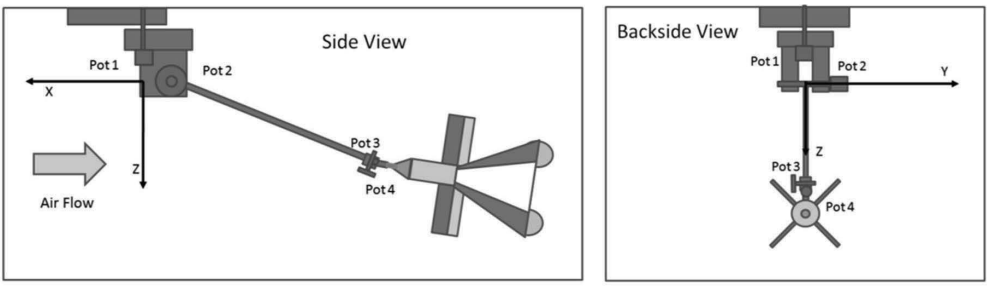


Figure 8. Drogue dynamic test rig and gust generator in WMU ADWT.

break the friction force. If the control surface module is fixed to the drogue which rotates relative to the hose, it causes substantial difficulties in generating required actuation forces from the control surface module as it constantly rolls. In this study, both a fixed roll and a free roll joint configuration between the hose and the drogue are investigated through dynamic testing in the wind tunnel.

The four control surfaces are coordinated to control roll, horizontal and vertical position, and drag producing mode. In order to achieve the control coordination shown in Fig. 5, a set of four servo actuators are implemented to work on the flap on each surface, and a servo mixer is used to program the required coordination. This servo mechanism is placed internal to the hose-drogue coupling housing of the scale model with a control processor module. An integrated control processor module is designed as shown in Fig. 6, which composed of an 8 bit μ-processor, micro-electro-mechanical system (MEMS) based inertial measurement unit (IMU), and a Bluetooth modem.

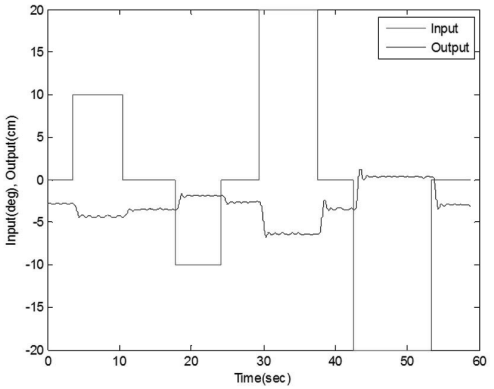
2.3 Dynamic test rig

In order to study the dynamic motion of the hose-drogue system and the effectiveness of the aerodynamic control surface module in a controlled environment, a drogue dynamic test rig is designed and manufactured as shown in Fig. 7. The rig basically represents a hose-drogue system in terms of a four degree-of-freedom (DoF) single link pendulum model. It consists of a base-frame which mounts on the ceiling of the wind tunnel; a 3ft length rigid bar of circular cross-section with one end connected to the drogue; and two universal joints with the total of four potentiometers. These potentiometers are connected to a 14 bit 5Ks/sec data acquisition system, providing accurate information on the position, and yaw and pitch orientation of the drogue.

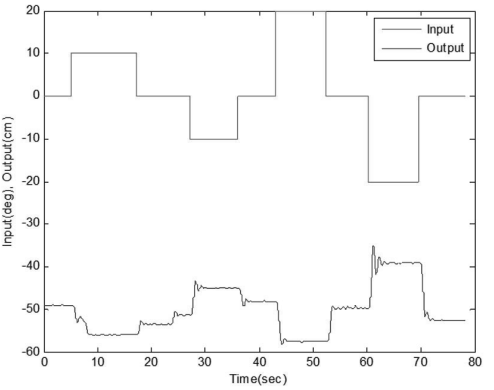
3.0 WIND-TUNNEL EXPERIMENT

In order to design an active control system to stabilise and control the drogue motion, it is necessary to obtain a representative dynamic model for feedback control law design. In this study, system identification technique is used to obtain a dynamic model of the test rig, and classical control design method is used to obtain a feedback control law for aerodynamic control surface module. To evaluate the performance of the closed-loop system, a gust generator is fabricated and placed in the wind tunnel, which is basically two movable flat plates connected to remote control servos. Depending upon its deflection configuration (symmetrical or asymmetrical of two plates), the flow field around the drogue is disturbed causing the drogue to move substantially large in vertical or in lateral direction. Figure 8 shows an overall picture of the test rigs and the gust generator installed in the Advanced Design Wind Tunnel (ADWT) at Western Michigan University.

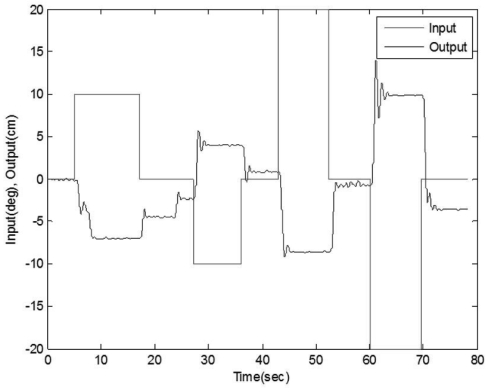
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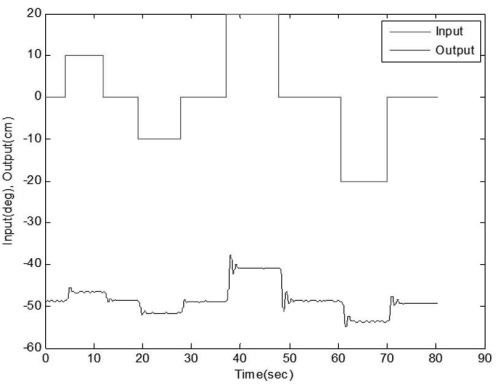
(a) Cross (×) Characteristics
(Input : δ_y, Output: *y*- position)



(b) Cross (×) Characteristics
(Input : δ_z, Output : *z*- position)



(c) Cross (+) Characteristics
(Input : δ_y, Output: *y*- position)



(d) Cross (+) Characteristics
(Input : δ_z, Output : *z*- position)

Figure 9. Open-loop testing.

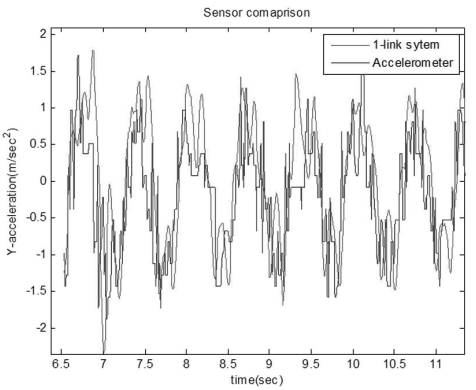


Figure 10. Acceleration signal comparison.

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3.1 Open-loop wind-tunnel testing

As mentioned earlier, the rolling motion of the drogue relative to the hose (which corresponds to the rigid bar in the test rig) causes significant difficulties in coordinating the aerodynamic control surface module as it is fixed to the coupling portion of the drogue assembly. It seems that the roll motion of the drogue does not appear significant in the conventional aerodynamically stabilised drogue, but it should be significant if the aerodynamic surface control module is implemented. For this reason, two joint configurations are tested; roll-fixed and roll-free, and the following observations are made: ·

- roll-free configuration showed that the roll-mode actuation of the control surface module was very effective generating substantially high roll-rate of the drogue, and some gyroscopic stabilisation effect was observed
- roll-free configuration revealed that the control surface module had a natural tendency to adjust its orientation into the cross (×) configuration in steady-state
- it was unable to generate the required vertical or lateral actuation force from the control surface module (for both × and + configuration) with roll-free configuration due to its rotational motion

Since the control surface module is unable to generate the desired control force with the roll-free configuration, the rest of the test and design study is carried out with the drogue roll being fixed. Two control configurations, as illustrated in Fig. 5, of the aerodynamic control surface module are tested. Figure 9 shows the results of open-loop response of the drogue to the vertical and lateral inputs from the control surface module. It is interesting to observe that, given 20° control surface input in side force mode the cross (×) configuration results in the drogue displacement of 4·5cm while the plus (+) results in 8·5cm. Regarding the vertical channel, the cross (×) configuration results in 10cm while the plus (+) results in 9cm. These results physcially make sense since the plus (+) configuration should be naturally efficient in generating aerodynamic force in side way.

3.2 System identification

To develop a feedback control law for the actively stabilised drogue system, system identification technique is employed to the open-loop test results to obtain representative system transfer functions for control synthesis. While the drogue position control as well as stabilisation is desired, the position control requires an accurate sensing of randomly moving drogue in flight. It is possible to measure the drogue position accurately to some extent, but the required sensing can be costly. Therefore, the design effort in this study is focused upon the drogue stabilisation by regulating the acceleration level of the drogue motion. This type of measurement is less costly and feasible for a low cost application targeting toward a remote control aircraft flight test.

The first attempt made in this study is to use the signals measured from the accelerometers mounted in the drogue as illustrated in Fig 6. The accelerometers (Analog Device, ADXL335, ±3g) were able to pick up the disturbance signals caused by the drogue motion, but the data quality is not suitable for feedback control design. or this reason, acceleration signals are reconstructed from the potentiometer signals through numerical differentiation based on the five point method for the first derivative,

Figure 10 shows the comparison between the accelerometer signals and the reconstructed acceleration signal through numerical differentiation. It shows overall trend in agreement, but the accelerometer signal shows saturation thus not suitable to be used for feedback control design.

Analysing the recorded signal, a time delay of 0·3sec has been observed which may arise from communication delay and processing time. This delay value is inserted in system identification

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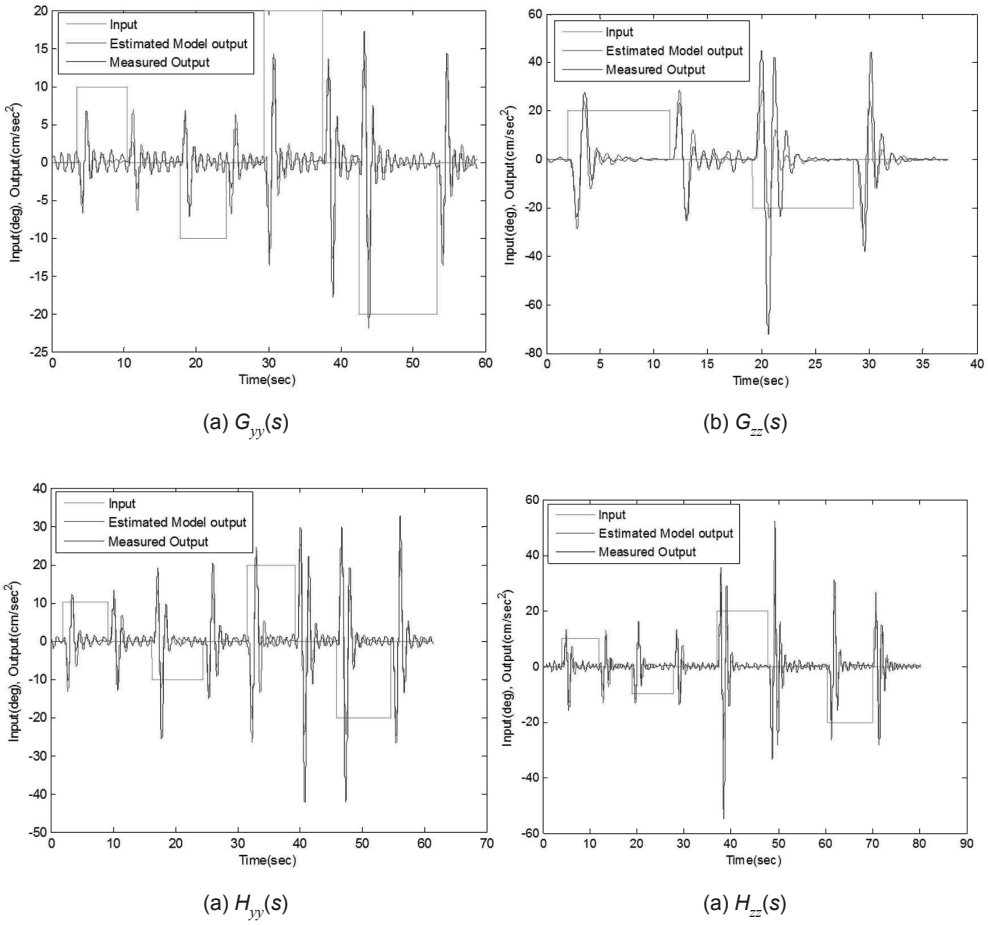


Figure 11. Response comparison: actual system vs transfer function model with delay.

process. Using System Identification Toolbox in MATLAB, a 4th order transfer function for each channel is obtained as summarised in Table 1.

Figure 11 shows the time domain response of the transfer function model with the time delay compared to the actual measurement. Figure 12 shows the transfer function error. The transfer function model adequately represents the actual system in terms of frequency characteristics, but somewhat larger difference in peak values. This may arise from some frictions in each joint and numerical error in the differentiation process.

3.3 Control law synthesis

Using the transfer functions obtained through system identification technique, a simple proportional-integral (PI) controller is designed as summarised in Table 2. Since the time delay is significant, Padé approximation technique is used to include the delay effect in the feedback control design process. In the following section, these control laws are implemented in the notebook computer equipped with LABVIEW, which enables to implement the designed controller to generate the desired servo signals.

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Table 1
System transfer functions

Control Configuration	Name	Input	Output	Transfer function
Cross (×)	$G_{Cy}(s)$	δ_y	a_y	$G_{Cy}(s)=\frac{-0{\cdot}05051s^4+10{\cdot}97s^3-171{\cdot}7s^2-352{\cdot}4s+34{\cdot}5}{s^4+3{\cdot}395s^3+49{\cdot}86s^2+84{\cdot}63s+379{\cdot}8}$
	$G_{Cz}(s)$	δ_z	a_z	$G_{Cz}(s)=\frac{0{\cdot}02595s^4-5{\cdot}121s^3-3{\cdot}323s^2-2{\cdot}063s+41{\cdot}46}{s^4+3{\cdot}665s^3+54{\cdot}4s^2+102{\cdot}6s+552{\cdot}8}$
Plus (+)	$G_{Py}(s)$	δ_y	a_y	$G_{Py}(s)=\frac{-0{\cdot}0841s^4+17{\cdot}68s^3-167{\cdot}4s^2-1,054s+24{\cdot}36}{s^4+3{\cdot}714s^3+46{\cdot}68s^2+85{\cdot}02s+400{\cdot}8}$
	$G_{Pz}(s)$	δ_z	a_z	$G_{Pz}(s)=\frac{-0{\cdot}2985s^4+59{\cdot}95s^3-263{\cdot}3s^2+43,040s+226{\cdot}1}{s^4+1{\cdot}57s^3+742s^2+1,153s+13,710}$

Table 2
PI controller

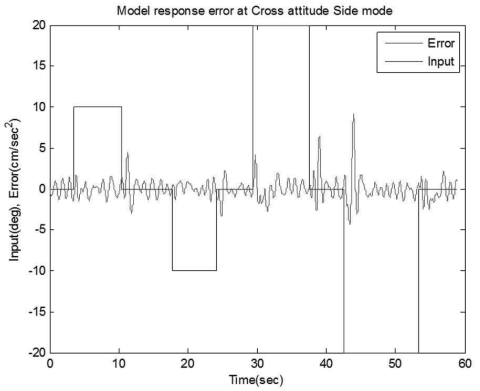
$K(s)=k_P+\frac{k_I}{s}$		
	k_P	k_I
$K_{Cy}(s)$	0·068481	0·3261
$K_{Cz}(s)$	0·0362018	0·11678
$K_{Py}(s)$	0·029976	0·14988
$K_{Pz}(s)$	0·0509864	0·29992

3.4 Closed-loop wind-tunnel testing

In order to evaluate the control system performance in the wind tunnel, artificial flow disturbances are generated by the gust generator shown in Fig. 8. Two control configurations (Cross and Plus) are tested, and Fig. 13 and Fig. 14 summarises the experimental results of the cross configuration control surface and the plus configuration control surface, respectively, in the presence of flow disturbance.

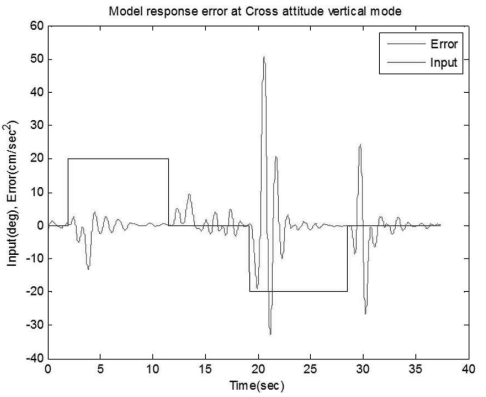
Shown in Fig. 13(a), the active control system (Cross configuration control surface) clearly demonstrates its functionality of reducing the magnitude of the drogue motion. Computing the

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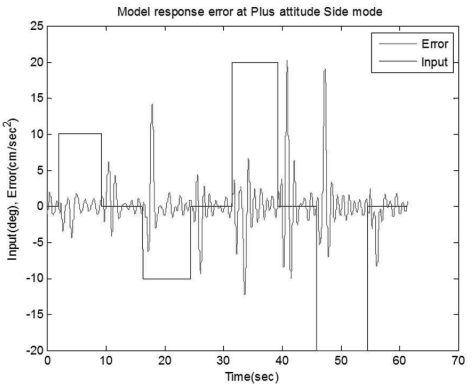
(a) $\Delta G_{yy}(s)$

Peak Error = 9·2290cm/sec^2
Mean Error = 0·8930cm/sec^2



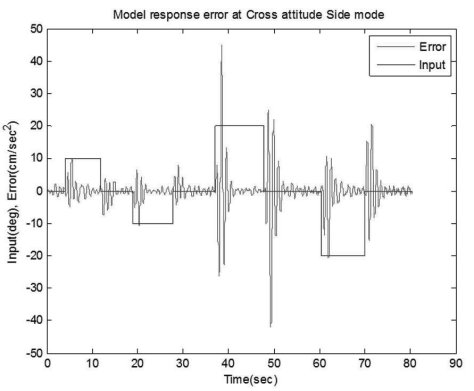
(b) $\Delta G_{zz}(s)$

Peak Error = 50·9201cm/sec^2
Mean Error = 3·1771cm/sec^2



(a) $\Delta H_{yy}(s)$

Peak Error = 20·2445cm/sec^2
Mean Error = 1·8566cm/sec^2



(a) $\Delta H_{zz}(s)$

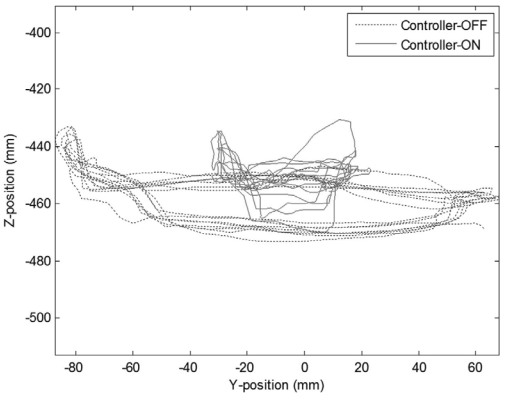
Peak Error = 44·7828cm/sec^2
Mean Error = 2·5858cm/sec^2

Figure 12. Transfer function model error.

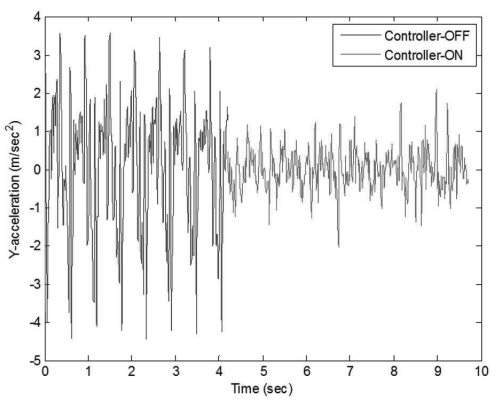
RMS values of the drogue displacement and acceleration, the active control system reduces the displacement magnitude by 68% (49·51mm to 15·94mm) and the acceleration magnitude by 55% (1·8m/s^2 to 0·798m/s^2). Comparing the acceleration levels in lateral (Fig. 13(b)) and vertical (Fig. 13(c)) direction, the reduction in the lateral direction is noticeable comparing to the vertical direction. Figures 13(d) and 13(e) shows the control input signals in all four servo channel and collective control of side and vertical mode control. In all cases, the actuation signals show no signs of saturation and its RMS value is about 4·33° which is well within the actuation limit of 20°. The vertical control signal is relatively low comparing to lateral, which could imply that the vertical channel controller ($K_{zz}(s)$) may be under actuated and improved for better performance.

Shown in Fig. 14(a), the active control system (Plus configuration control surface) also clearly demonstrates its functionality of reducing the magnitude of the drogue motion.

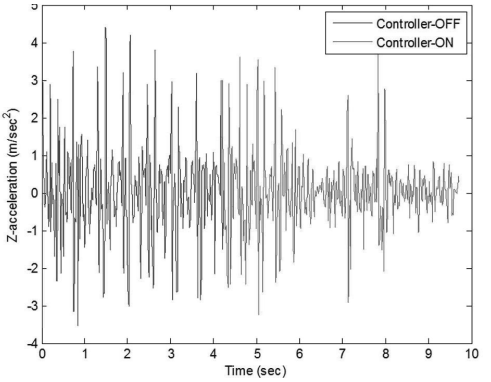
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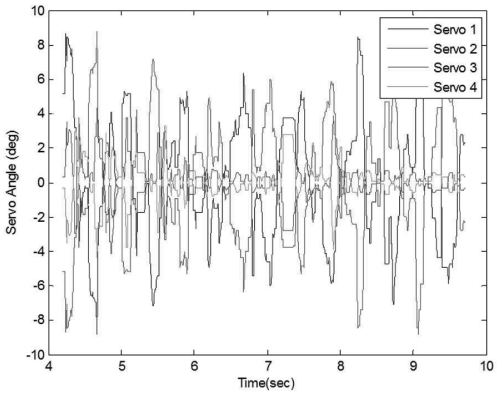
(a) Drogue trajectory



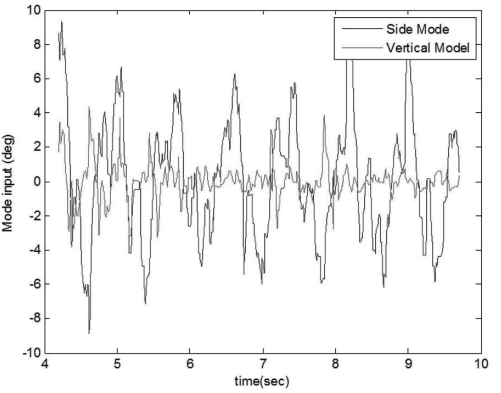
(b) *Y*-acceleration



(c) *Z*-acceleration



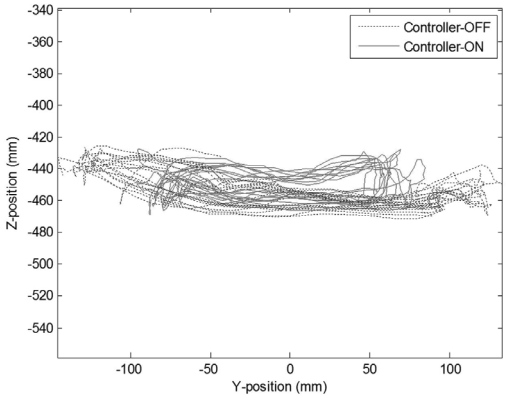
(d) actuation (servo) signals



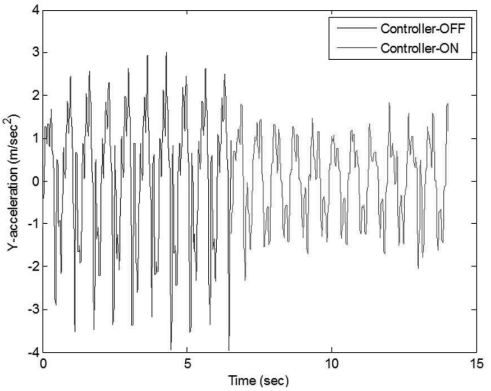
(e) control mode signal

Figure 13. Closed-loop system characteristics: cross (×) control configuration.

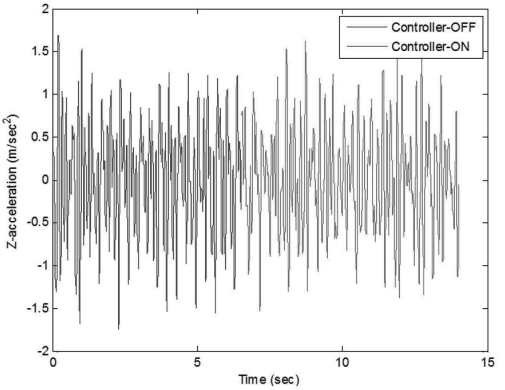
https://doi.org/10.1017/S0001924000008721 Published online by Cambridge University Press



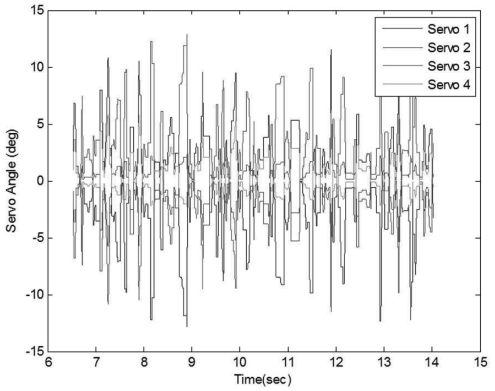
(a) Drogue trajectory



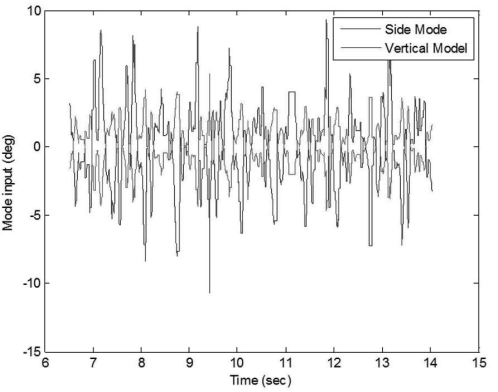
(b) *Y*-acceleration



(c) *Z*-acceleration



(d) actuation (servo) signals



(e) control mode signal

Figure 14. Closed-loop system characteristics: plus (+) control configuration.

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Computing the RMS values of the drogue displacement and acceleration, the active control system reduces the displacement magnitude by 40% (83·77mm to 51·06mm) and the acceleration magnitude by 35% (1·49m/s^2 to 0·98m/s^2). Comparing the acceleration levels in lateral (Fig. 14(b)) and vertical (Fig. 14(c)) direction, the reduction in the lateral direction is noticeable while the vertical accelerations seems no change or even increased. Figures 14(d) and 14(e) shows the control input signals in all four servo channel and collective control of side and vertical mode control. In all cases as in the Cross configuration case, the actuation signals show no signs of saturation and its RMS value is about 5·52° which is well within the actuation limit of 20°.

Comparing the drogue trajectory of Fig. 13(a) and Fig. 14(a), the Plus configuration exhibits relative large displacement in lateral direction for the similar reason discussed earlier. The vertical control surface might lose control effectiveness as the drogue has somewhat large of attack relative to free-stream. However, technical issues such as delays, numerical errors, etc., in the aspects of instrumentation and control could play a substantial role. In general, it can be conclude that the Cross control surface configuration is advantageous comparing to the Plus control configuration.

4.0 SUMMARY AND CONCLUSION

In this paper, an active control of refuelling drogue in hose-drogue-probe refuelling system is considered. A ⅓ scale model of a conventional aerodynamically stabilised drogue and a set of four aerodynamic control surface fixed to the coupling portion of the drogue system is fabricated. To carry out dynamic testing in the wind tunnel, a dynamic test rig is also fabricated. Two control surface configurations are tested, and system identification technique is used to obtain necessary transfer function models for feedback control law synthesis. Proportional-Integral controllers are designed based on the transfer function models, and implemented in the LABVIEW based control and instrumentation computer which is connected to the onboard remote control servo actuators. Closed-loop dynamic testing is carried out by generating artificial flow disturbance made by a gust generator mounted in the wind tunnel. The closed-loop dynamic testing showed the effectiveness of the aerodynamic control surface module, which reduces the drogue motion by 68% in terms of RMS magnitude with the Cross control surface configuration.

There are many technical issues to be addressed for this active control concept to be applied to a real system. First, the orientation of the control surface module is very important which depends on accurate measurement of inertial acceleration of the drogue. Since the drogue undergoes rolling motion relative to the hose, the control surface module may also rotate if it is fixed to the any portion of the drogue body. This roll motion also causes difficulty in measuring inertial acceleration as the accelerometers may rotate together with the drogue body. An attitude-heading-reference-system (AHRS) could be a possible sensor, but installing such a sensor module is limited by relatively small space in the drogue.

Future works for continuation of the current study are in progress which includes: 1) further refining the PI controller through experimental testing, 2) increasing analogue-to-digital conversion (ADC) resolution and improving sensor qualities to increase the level of signal-to-noise (SNR), 3) developing a mathematical model of the test rig to obtain more accurate control design model, 4) carrying out flight test using a remote control aircraft.

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