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WIND TUNNEL SIMULATION OF COMBAT AIRCRAFT MANOEUVRES

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Abstract

The need for a multiple degree-of-freedom large-amplitude motion capability for dynamic wind tunnel testing is discussed, and existing rigs briefly reviewed. Two novel rig concepts under development within DERA are presented: the six degree-of-freedom 'forced motion' Large-Amplitude Motion Rig and the five degree-of-freedom 'free motion' Pendulum Suspension Rig.

Introduction

Aircraft designed for low-observability are likely to suffer aerodynamic penalties which may affect manoeuvrability and it would be prudent to identify adverse design features in advance of the procurement process. To enable prediction of the flight dynamics of candidate configurations it is necessary to develop mathematical models and simulations with accurate aerodynamic data, giving advanced warning of possible problem areas and also identifying favourable aerodynamic features.

Practical predictions of dynamic air loads using CFD at flight conditions where appreciable flow separation occurs is not an immediate prospect; for the foreseeable future wind-tunnel based techniques coupled with appropriate mathematical models will be required to generate aerodynamic data for simulator based evaluations of combat aircraft flight characteristics. The experimental requirements for wind tunnel dynamic testing are inseparable from the form of the mathematical model used, which in turn is governed by the nature of the aerodynamic characteristics and by the aircraft manoeuvre envelope.

For conventional aircraft configurations at low angles of attack the aerodynamic characteristics are reasonably linear and the linearised stability derivative or aerodynamic transfer function models can be applied. The usual experimental technique utilised is to measure the aerodynamic loads on an aircraft model undergoing a forced small-amplitude oscillatory motion in a single degree-of-freedom. Most existing dynamic wind tunnel rigs are of this form, although rotary (pitch, yaw, roll) mechanisms greatly outnumber the mechanically more complex translational (heave, sway) motion modes. It should be noted that the majority of rotary mechanisms give a combined motion, in which for example, pitch rate q and rate of change of angle of attack $\dot{\alpha}$ are coupled. Pure rotary motion can be achieved using a 'snaking' mechanism, but this is again mechanically complex and such rigs are rare.

Unfortunately, the aerodynamic characteristics of low-observable configurations are highly non-linear, whilst combat manoeuvre envelopes have extended into the high-rate, large-amplitude, non-planar motion regime. In this case, a large-amplitude motion dynamic test capability is necessary, although the number of degrees-of-freedom depends on the manoeuvre envelope to be considered. One concept often applied is that of 'characteristic motions' [1], whereby non-linear, non-planar aerodynamic characteristics can be built up from four simple model motions - (i) steady angle of attack and sideslip, (ii) pitch oscillations, (iii) yaw oscillations and (iv) steady coning (roll about the velocity vector). However, two assumptions are implicit in this approach, firstly that the aerodynamic response functionals have a linear dependence on angular rates and secondly that the vehicle flight path is nearly rectilinear.

The first is well-known and based on the further assumptions of slowly varying motion and the absence of rate-dependent hysteresis effects; the second is less well-known and is an inherent limit on the applicability of the 'characteristic motion' concept. One means of expanding the concept is to use an oscillatory coning motion, with the axis of rotation offset from the velocity

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vector [2], but this is still limited to aircraft motions which do not vary greatly from the experimental trajectory. A further difficulty with the concept is the need for several dedicated test rigs. This is not only expensive but can lead to further uncertainties due to the sensitivity of high angle-of-attack aerodynamic characteristics to model support structure interference [3].

To address both the limitation to certain aircraft trajectories and the need for a number of separate test rigs, a large-amplitude motion dynamic test rig is required, capable of arbitrary motion profiles in five or six degrees-of-freedom. To that end, a development programme for such a rig was set in motion by the Defence Evaluation and Research Agency in 1996. This paper reviews existing multiple degree-of-freedom dynamic rigs, and presents two novel concepts for six degree-of-freedom 'forced motion' and five degree-of-freedom 'free motion' wind tunnel testing.

Review of Existing Rig Mechanisms

Detailed descriptions of a wide range of previous, current and planned dynamic wind tunnel test rigs may be found in references 4 and 5, which concentrate on larger governmental facilities. The majority of large-amplitude motion rigs are basic single degree-of-freedom mechanisms, moving in plunge, pitch or roll. For multiple degree-of-freedom motion a wide range of ingenious mechanisms have been utilised, the most important of which are briefly described below.

Yaw + roll

An unusual mechanism recently developed at Stanford University [6] provides two degree-of-freedom motion in yaw and roll, Figure 1. The novel aspect of this device is that the mechanism inertias and friction are compensated for using two servo motors with torque and acceleration feedback. This provides effectively free motion without the need for high cost low-friction bearings, coupled with the capability to measure aerodynamic loads directly.

Plunge + pitch + roll

A rig developed at the Virginia Polytechnic Institute, Figure 2, provides three degree-of-freedom motion [7]. A plunge actuator moves a carriage running vertically along linear bearings. A roll actuator is mounted on a pitch actuator, which is in turn mounted on the carriage. The moving structure is massive, with the carriage and model weighing over 400kg. The combination of pitch and plunge enables both pure plunge (q = 0) and pure pitch (α = 0) motions. However, the location of the pitch axis aft of the model also results in an accompanying fore-and-aft motion.

Planar Motion Mechanisms

A two degree-of-freedom mechanism is provided by a twin pushrod arrangement [8], enabling combined pitch and plunge motions to be achieved as shown in Figure 3. Again, small fore-and-aft motions of the model are unavoidable. A five or six degree-of-freedom mechanism can be derived from this basic configuration by mounting the two pushrods upon a twin leadscrew/slideway arrangement, to give a lateral motion (yaw and sway) capability. This mechanism is ideally suited to use in a tow-tank [9], mounted from a carriage whose speed can be varied to provide a sixth degree-of-freedom, as in the IMD Marine Dynamic Test Facility shown in Figure 4.

Gimballed mounts

A twin gimbal plus a sting shaft roll actuator is the intended final configuration of the three degree-of-freedom ONERA 'pqr' rig [10], Figure 5. Currently this rig provides dynamic motion in the pitch degree-of-freedom only. An open-jet working section is required for the application of this mechanism. A number of 'free-motion' gimballed rigs exist, with a model mounted on a two or three degree-of-freedom spherical bearing. These can be either 'free-to-rotate' [11] or driven by auxiliary aerodynamic surfaces, Figure 6 [12].

Wire suspensions

Multiple degree-of-freedom small-amplitude oscillatory tests have been carried out using wire-mounted models [13] with and without active cable control. However, control of the system and estimation of stability derivatives becomes more and more complex as the number of degrees-of-freedom increases.

Magnetic suspensions

The ultimate in dynamic test facilities would be a magnetic suspension rig, and indeed such a device has been used at Southampton University for coning tests of a small Harrier model. Unfortunately, cost and technical difficulties with model trajectory control for arbitrary motion have precluded the practical application of the concept.

The Large-Amplitude Motion Rig

The Large-Amplitude Motion Rig is a six degree-of-freedom 'forced motion' rig currently under development for the 13ft x 9ft low-speed wind tunnel at DERA Bedford, with a novel mechanical configuration based on the Stewart Platform commonly used in flight simulators. The rig was originally intended to utilise existing lightweight sting-mounted models designed for the small-amplitude single degree-of-freedom motion Inexorable Drive Rig [14] (IDR) facility at DERA Bedford, along with the IDR sting and integral five-component balance assembly.

Based on a survey of existing large-amplitude motion rigs, potential full-scale manoeuvre capabilities and requirements for frequency domain aerodynamic model identification, target model motion parameters were ± 30° in pitch, ± 15° in yaw and ± 60° in roll, along with ±

0.5m in heave, sway and surge, all at non-dimensional frequencies up to 0.5.

For a representative full-scale combat aircraft, at typical manoeuvring speeds, these would equate to angular velocities of the order of 360°/s and motion frequencies of the order of 1.5Hz. For a lightweight dynamic model sized for the 13ft x 9ft tunnel, with a root chord of 1.0m tested at 30m/s, corresponding angular velocities would be of the order of 500°/s and motion frequencies of the order of 2.5Hz.

Configuration Selection

The 'conventional' rig configurations capable of extension to five or six degrees-of-freedom all suffer from the disadvantage of being *serial* mechanisms. The end results are low payload/structure weight ratio and hence high actuator power requirements.

An unconventional (in a wind-tunnel application) *parallel* mechanism for providing six degree-of-freedom motion combined with rigidity, quick response and high payload/weight ratio is the Stewart platform [15], widely used for flight simulators and robotic manipulators.

In flight simulator applications the Stewart platform consists of a triangular platform mounted upon six actuators arranged in three pairs, Figure 7b. Each actuator pair is attached to one corner of the platform by a common three-axis joint. Each actuator is connected to the floor by a two-axis joint. Within each pair the floor joints have a common axis. Thus the position of each attachment point on the platform can be controlled within the plane containing the actuator pair. The 'uncontrolled' rotation of this plane about the common axis is determined by the 'controlled' positions of the other two attachment points.

The Stewart platform can be adapted for use as a wind-tunnel model support system by mounting a model from the platform on a conventional sting. However, the 'six-post' configuration used for flight simulators is too bulky for installation in a wind-tunnel, whilst the vertical displacement of the platform is limited by the actuation hardware, which in turn limits the angle through which a model mounted ahead of the platform can be rotated.

These difficulties are overcome by replacing each symmetric actuator pair by a primary actuator controlled in a side-to-side motion by a secondary actuator, Figure 7c. The primary actuator rod end is attached to the platform corner with a three-axis joint, and to the working section floor with a two-axis joint at the upper end of the cylinder. The cylinder of the primary actuator and the entire secondary actuator are now below the floor of the working section, and the platform is supported by three rather than six struts. The blockage levels of the structure are considerably reduced and the motion envelope increased.

The modified Stewart platform arrangement has a number of advantages which make it ideal for a large-amplitude forced-motion rig:

- *full six degree-of-freedom motion* - with the possibility of adding a sting roll actuator to give an additional capability.
- *high payload/structure weight ratio* - parallel mechanism.
- *low support interference* - no rig structure behind the model, coupled with reducing blockage levels with increasing angle of attack.
- *high stiffness* - triangulated structure, with stiffness increasing with angle of attack.
- *versatility* - a wide range of applications (eg static tests, stores separation, tanker/receiver interference, dynamic ground effect, STOVL, simulation of aircraft trajectory from flight test data).
- *ease of installation* - the mechanism can be mounted from the existing tunnel structure with minimum modification.

These advantages are also relevant to model support systems for conventional steady-state wind tunnel testing; as a result, a six degree-of-freedom *static* model support system based on the Stewart Platform mechanism is now under development by FFA in Sweden for their LT1 low-speed wind tunnel.

Analysis of Rig Mechanism

Kinematic analysis of the Stewart platform mechanism applied as a robotic manipulator has received considerable attention in recent years. The analysis of the general case is complex; fortunately the modified mechanism shown in Figure 7 permits considerable simplification of the governing equations [16].

The analysis can be divided into two parts - the *inverse* kinematics and the *forward* kinematics. The inverse problem is that of determining the six actuator lengths for a given model position and attitude, which for a parallel mechanism is a straightforward operation involving a sequence of vector additions and rotations.

This solution is sufficient for basic sizing of the rig mechanism. However, analysis of the dynamic behaviour of the mechanism requires the solution of the forward kinematic equations - ie the determination of the model position and attitude for a given set of actuator lengths. The forward kinematic solution involves coupled non-linear equations with multiple roots, requiring a numerical rather than analytical solution.

Two related features of the rig mechanism emerge from this analysis:

a. *multiple assembly modes* - for any given set of actuator lengths there are up to 16 different ways of assembling the mechanism.

b. *singular positions* - for certain model positions and attitudes the forward kinematic equations become singular and the mechanism gains a degree of freedom.

Multiple assembly modes are not in themselves a problem, since they are generally widely separated and most are precluded by practical limits on the mechanism. Singular positions correspond to a repeated root of the forward kinematic equations; although at a singularity the mechanism becomes unrestrained, in practice rapidly increasing actuator loads will prevent such a position being achieved. A number of singularities lay within the preliminary design envelope, leading to changes to the dynamic design points during the design process.

Design of Rig Mechanism

Design of the large-amplitude motion rig mechanism has been undertaken for DERA Bedford by Frazer-Nash Consultancy Ltd, with the control system hardware and software developed by Cambridge Control Ltd. A primary design tool was the SDRC 'I-Deas' Master Series 3D modelling software package. Using this package a 3D solid model of the rig mechanism was generated, which could be driven through a range of design motions.

The resulting motion system design (Figure 8) consists of four sections:

a. *actuators* - hydraulic actuators were chosen because they offered the necessary level of controllability while satisfying the power requirements; however, these have had to be designed specifically for this application. Of particular concern were the large side loads that had to be carried by the primary actuators and the high flow rates necessary to achieve peak velocities of the order of 5m/s.

   Four-axis joints between the primary actuator rods and the top platform have been designed to accommodate up to ± 85° actuator rod offset and to be as compact as possible. The additional degree-of-freedom allows the elements of the joint to align themselves with the direction of motion when the joint angle exceeds 45°.

b. *base triangle* - the size and position of the base triangle of the motion system was controlled by a number of conflicting parameters, in particular the size, layout and orientation of the existing turntable and the primary actuator motions resulting from required model motion envelope.

   The base triangle assembly is of welded steel construction, with the actuators are mounted in pairs of gimbal blocks that lie on the free axis of each actuator pair.

c. *top triangle* - the top platform is based on a equilateral triangle between the actuator joint pivot points, sized to be large enough to allow a reasonable degree of control and small enough to maximise the motions that could be produced with the limits of actuator performance. Welded aluminium construction with standard box section is used to minimise the mass whilst maintaining structural strength.

d. *sting and model* - initially, the existing IDR sting and models will be used.

Current Status And Plans

Cost overruns due to the high level of installed hydraulic power required (>300kW) and technical problems with the demanding primary actuator specification have resulted in a postponement of the wind tunnel rig commissioning programme. An extended risk reduction exercise is underway, consisting of the fabrication of a 1:4 scale pilot rig, followed by installation of the full-scale rig in a hydrodynamic test facility - the large ship tank at DERA Haslar.

The small-scale pilot rig will use off-the-shelf electric linear actuators, and will be installed in the 4ft x 3ft low-speed tunnel at DERA Bedford as a *static* model positioning system. Tests on this rig will serve to confirm the rig concept, verify the kinematic analysis of the mechanism, and commission the control system hardware and software. In addition the rig will provide a useful test capability for the 4ft x 3ft and in the longer term will be installed in a small water tunnel as a *dynamic* test facility.

Having confirmed the basic rig concept, the next step is to commission the full-scale rig. To avoid the cost and technical risks associated with the hydraulic actuators it is intended to use the DERA Haslar ship tank, with the rig mounted inverted from the towing carriage, Figure 8.

Operation in water, at low freestream velocities and with large models, permits dynamic testing at non-dimensional motion parameters and at Reynolds Numbers similar to those possible in windtunnel experiments [17]. The primary advantage lies in the much slower actuator motions required, enabling conventional electrically driven ball-screw actuators to be used and hence greatly reducing technical risk, installed power requirements and overall cost. Speeds are low enough to avoid cavitation, while the tow tank cross-section is large enough (12m x 5m) to minimise free surface effects.

In addition to simply matching the capabilities of a wind tunnel, implementing the large-amplitude motion rig in a tow tank confers a number of very significant benefits:

- *low turbulence environment* - unlike a wind tunnel, the working fluid is stationary, so that turbulence levels are effectively zero and a better simulation of a flight environment is achieved.
- *increased safety* - reduced motion rates greatly decrease the chances of a mechanical problem,

whilst in the event of a catastrophic failure any sections of the rig or model breaking off would fall to the floor of the tank, causing no further damage.

- *low inertial loads* - reduced motion rates result in the inertial loads becoming negligible in comparison to the aerodynamic loads, thus greatly improving measurement accuracy.
- *reduced support deflections* - reduced inertial loads, and reduced frequencies, will greatly lessen the chances of dynamic support structure deflections.
- *non-intrusive flow measurements* - 'low-speed' operations in a tow tank are ideal for flow visualisation (using dyes, hydrogen bubbles and/or laser light sheets) and for non-intrusive flow measurements (laser doppler anemometry, particle image velocimetry etc). This is a particular advantage for dynamic tests, where flow visualisation and measurement in a wind tunnel environment is complex and costly.
- *increased user base* - multiple degree-of-freedom dynamic testing is already routinely used for submarine studies [9].

Following from successful commissioning tests in the tow tank, which would focus on the operating aspects of the rig (and associated control system and data acquisition) as a *dynamic* test facility, the mechanism will be moved back to the 13ft x 9ft wind tunnel as and when funding became available.

The Pendulum Suspension Rig

The Pendulum Suspension Rig is a five degree-of-freedom 'free motion' rig in the preliminary stages of development for the 13ft x 9ft wind tunnel. In contrast to the Large-Amplitude Motion Rig, this device aims to reproduce free-flight motions as closely as possible within the confines of a wind tunnel environment.

'Conventional' free-flight testing covers a wide range of techniques, from unpowered drop tests and powered radio-controlled models outdoors to catapult launched and tethered wind tunnel models indoors. All suffer from the uncontrolled, unpredictable nature of the free-flight environment, and from the technical difficulties inherent in reconstructing model trajectories and aerodynamic loads from on-board sensors and external video images.

Alternatively, a dynamically scaled wind-tunnel model mounted on a low-friction pivot with one to three rotary degrees-of-freedom provides a controlled experiment in a known environment and straightforward measurement of model attitude and total reaction force. With appropriate control surface motions, such a rig can generate a wide range of model motions from which, for example, trimmed lift, static and dynamic derivatives, and large-amplitude motion aerodynamic characteristics can be derived [11].

Rig Configuration

However, these mechanisms suffer from the basic problem of only providing coupled rotary motion, whereas translational motion is also necessary to match combat aircraft manoeuvre trajectories. The pendulum suspension rig addresses this lack by mounting a model on a rigid pendulum using a three-axis spherical joint. The pendulum is in turn attached to the wind tunnel working section wall with a two-axis joint, Figure 10. The model can be mounted upright or inverted. Model position is inferred from the joint positions, although care must be taken to allow for strut bending. Aerodynamic forces and moments can be determined from the model trajectory (coupled with the strut tension and bending loads) using standard flight test methodologies.

The dynamic response of such a five degree-of-freedom mechanism permits motions very similar to those found in flight; the similarities are close enough [18] to permit:

a. identification of unsteady aerodynamic characteristics from realistic spatial motions

b. control law design and assessment

The pendulum suspension rig has a wide range of advantages over conventional tethered or free-air free-flight testing:

- *controlled environment* - freestream velocity and turbulence levels known
- *safety* - no danger of loss of costly model due to departure/loss of control
- *rapid turn-around* - ad-hoc model geometry modifications can be made without need to reassess stability and controllability
- *consistency with forced oscillation tests* - similar or identical model, similar wind tunnel interference effects, similar freestream conditions
- *simple model trajectory measurement* - joint angles plus allowance for strut bending
- *no need for telemetry*
- *ease of implementation of engine simulation and novel control effectors*
- *long test duration* - improved quality of data
- *potential for high-speed testing* - low input power requirements

A significant additional advantage over conventional static wind tunnel testing is that trimmed aerodynamic characteristics can be determined directly.

Analysis of Rig Dynamics

A simple two degree-of-freedom pendulum support rig with an upright light aircraft model was tested in the TsAGI T-103 low-speed open jet tunnel in 1994, Figure 11 [19]. For certain combinations of model incidence and pendulum length the system was found to be dynamically unstable, generating large-amplitude limit-cycle oscillations. Although these oscillations were useful, in enabling the determination of dynamic aerodynamic characteristics for large-amplitude pitching and plunging motion, in general it would be desirable to avoid such instabilities.

An analysis of the mechanism dynamics [19] showed the pendulum instability to be dependent on trim angle of attack α_0, relative inertia μ ($= 2m/\rho Sc$), Froude Number Fr ($= v^2/gc$) and pendulum length $\bar{r}$ ($= r/c$), Figure 12. Two unstable regions were identified, both associated with large variations in equilibrium pendulum angle γ_0, but relatively small variations in model attitude and angle of attack. A potential autorotational motion was also identified. However, Figure 11 shows that these instabilities can be avoided using an inverted model suspension (ie negative equilibrium pendulum angle γ_0 and angle of attack α_0).

An analysis of the general five degree-of-freedom case of Figure 10 is more complex [18], with the offset of the model cg from the model pivot becoming important. With zero cg offset a one-parameter set of equilibrium solutions for a given angle of attack and sideslip exists, as shown in Figures 13 and 14. Two areas of instability exist, one at low angles of attack corresponding to loss of stability in the longitudinal modes, and one at higher angles of attack due to loss of stability in the lateral modes.

Once again, an inverted model suspension can be seen to be preferable, for both increased mechanical stability and reduced pendulum inclination variation.

Current Status and Plans

In order to assess the potential of the Pendulum Suspension Rig for low aspect-ratio configurations at high angles of attack, a pilot rig is under construction for the 4ft x 3ft low speed wind tunnel at DERA Bedford. This will use a scale model of the HP-115, a slender wing research aircraft flown in the UK in the 1960's which displayed a well-behaved and extensively analysed wing rock motion [20]. The model uses conventional radio-controlled hobby aircraft construction techniques, with electric ducted-fan propulsion. Free-flight tests will be undertaken to provide a qualitative comparison with the wind tunnel experiments.

A successful demonstration will lead onto the development of a larger-scale rig for the 13ft x 9ft wind tunnel.

It is also intended to examine the feasibility of applying the concept to high-speed (transonic and supersonic) dynamic testing, where existing rigs are both costly to operate and very limited in their test envelopes. A reduction in the number of degrees-of-freedom will be necessary, along with active or passive aerodynamic balancing of the pendulum strut.

Conclusions

Two novel and complementary concepts for large-amplitude dynamic testing at low speeds have been described: the 'forced motion' six degree-of-freedom Large-Amplitude Motion Rig and the 'free-motion' five degree-of-freedom Pendulum Suspension Rig.

The Large-Amplitude Motion Rig installed in the DERA Haslar ship tank will provide

- arbitrary, pre-determined and repeatable model trajectories
- low support interference
- excellent flow visualisation

and will be ideally suited to fundamental research into unsteady manoeuvring aerodynamics and the appropriate mathematical modelling and scaling methodologies.

The Pendulum Suspension Rig installed in the 13ft x 9ft wind tunnel at DERA Bedford will provide

- a close approximation to free-flight in a controlled and safe environment

and will be ideally suited for the design and assessment of novel control laws and effectors. In addition, the large-amplitude, high rate motion capability will provide additional data on basic aerodynamic characteristics.

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List of Symbols

b	wing span, m
c	wing chord, m
f	frequency, Hz
k	non-dimensional frequency, $2\pi fc/U$
p, q, r	angular velocity in body axes, rads^{-1}
U	freestream velocity, ms^{-1}
x, y, z	model location, m
α	angle of attack, deg
β	sideslip angle, deg
ϕ	cone angle (roll about velocity vector), deg
γ	longitudinal pendulum inclination, deg
λ	lateral pendulum inclination, deg

Abbreviations

DERA	Defence Evaluation and Research Agency, UK
FFA	Flygtekniska Försöksanstalten, Sweden
IMD	Institute for Marine Dynamics, Canada
IDR	Inexorable Drive Rig
ONERA	Office National d'Etudes et de Recherches Aerospatiales, France

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Figures

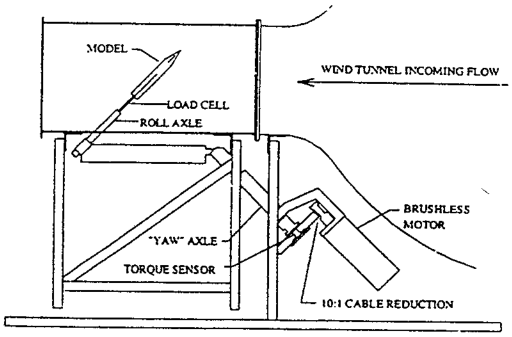


Figure 1 The Stanford two degree-of-freedom mechanism

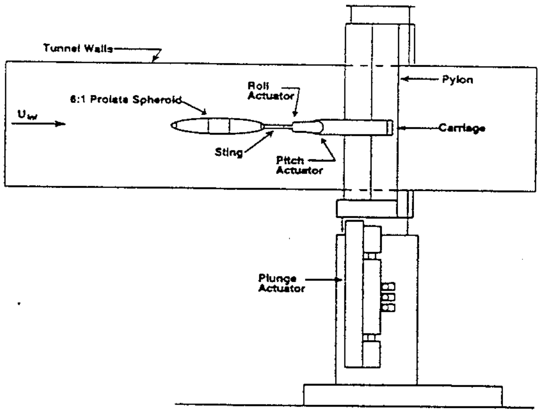


Figure 2 The 'DyPPiR' three degree-of-freedom mechanism

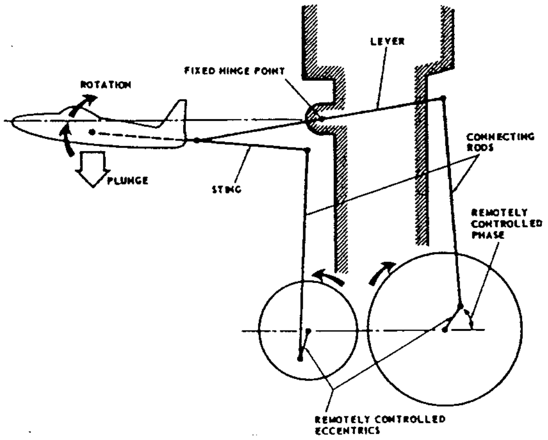


Figure 3 The CALSPAN two degree-of-freedom mechanism

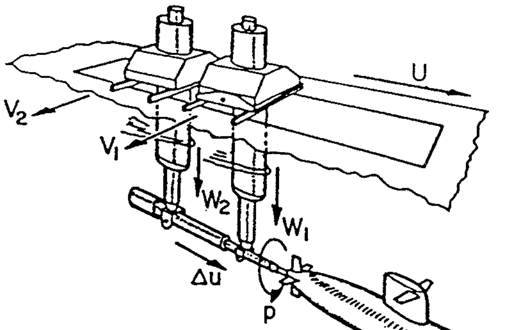


Figure 4 The Marine Dynamic Test Facility five/six degree-of-freedom mechanism

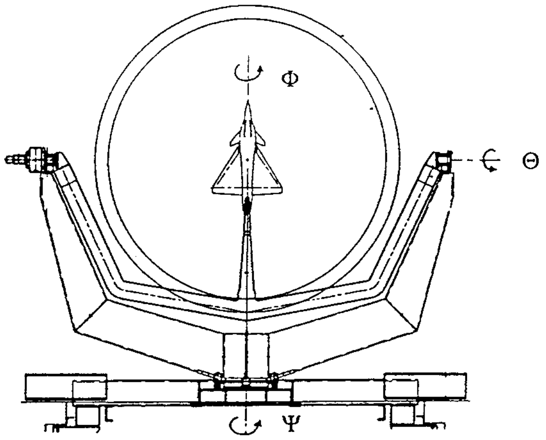


Figure 5 The ONERA 'pqr' three degree-of-freedom mechanism

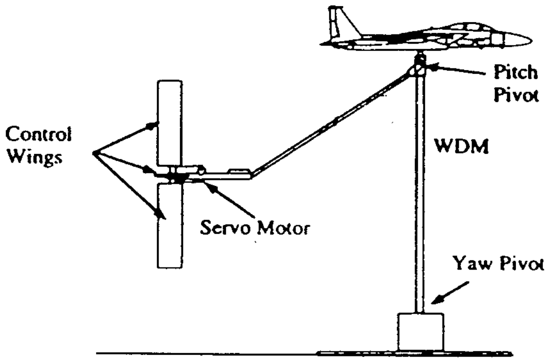
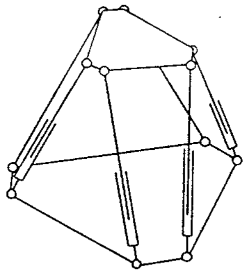
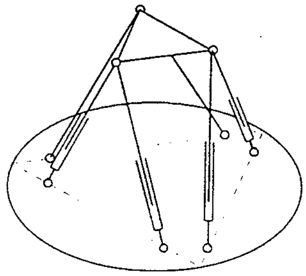


Figure 6 The 'Wind-Driven Dynamic Manipulator' two degree-of-freedom mechanism

a) general six-post Stewart platform



b) basic flight simulator mechanism



c) modified geometry

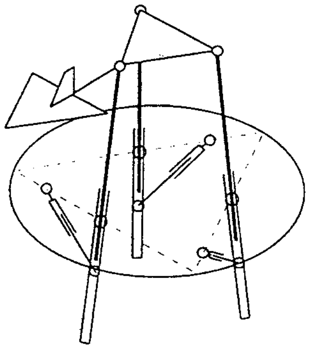


Figure 7 Application of Stewart platform mechanism as a model support system

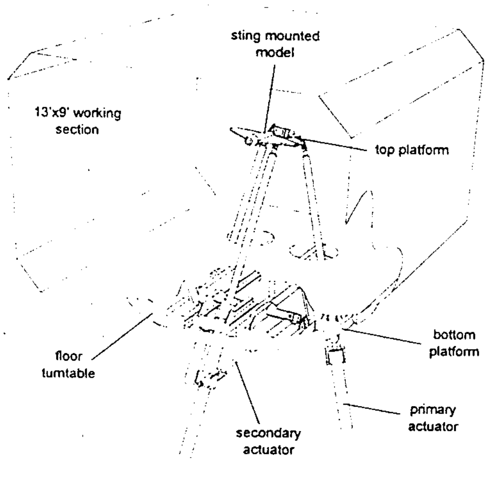


Figure 8 I-Deas model of the Large-Amplitude Motion Rig mechanism

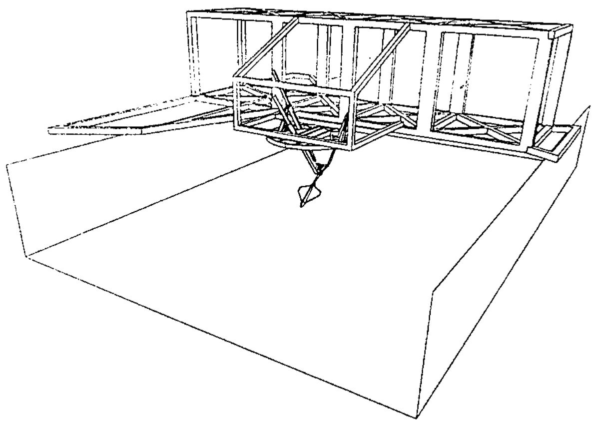


Figure 9 The Large-Amplitude Motion Rig in the DERA Haslar ship tank

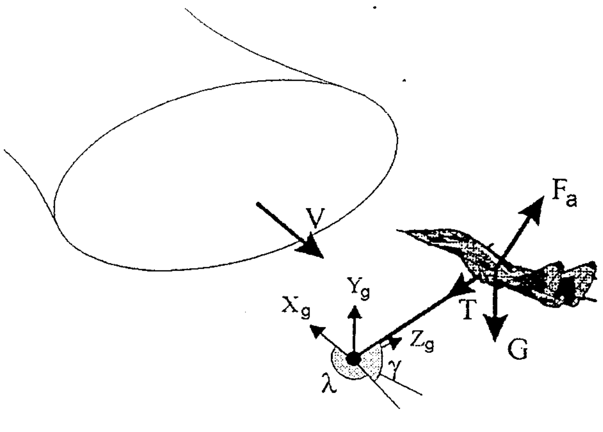


Figure 10 The five degree-of-freedom Pendulum Suspension Rig mechanism

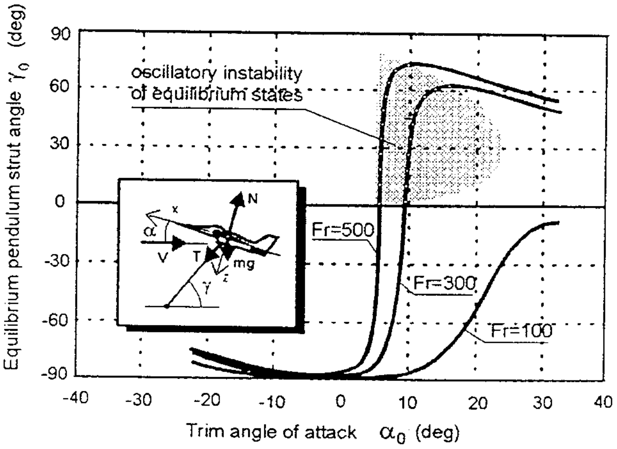


Figure 11 Dependency of strut equilibrium angle on trim angle of attack for an upright two degree-of-freedom Pendulum Suspension Rig

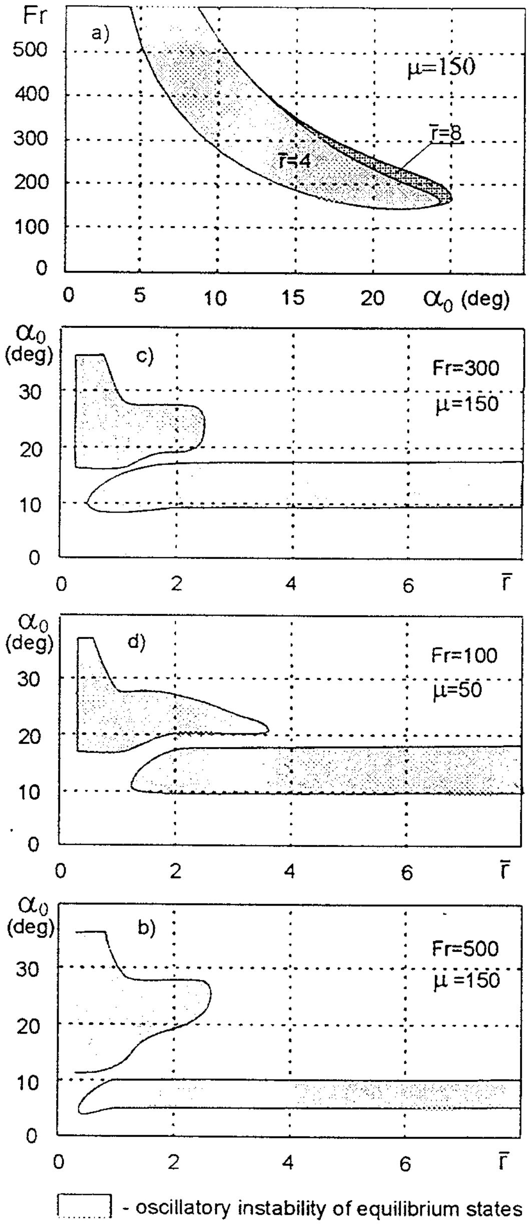


Figure 12 Instability regions for two degree-of-freedom upright model suspension

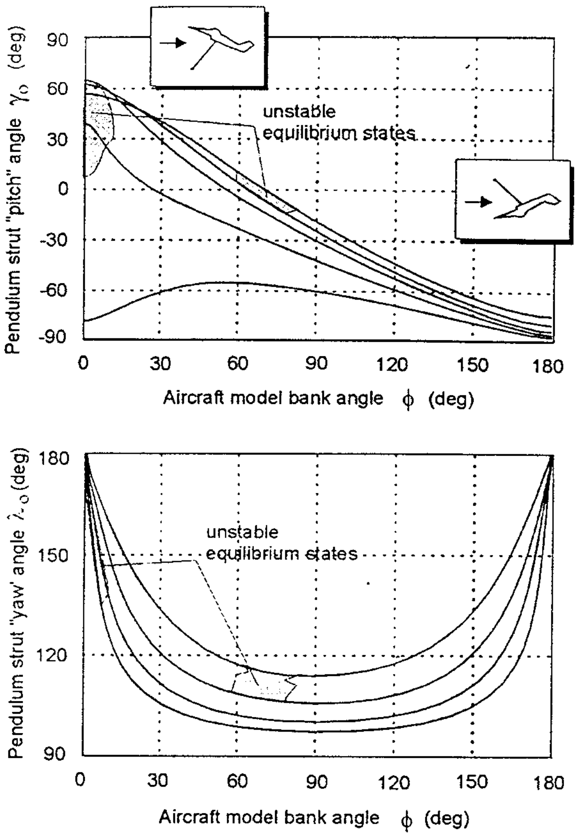


Figure 13 Equilibrium parameters and stability characteristics for five degree-of-freedom model suspension (cg at joint position)

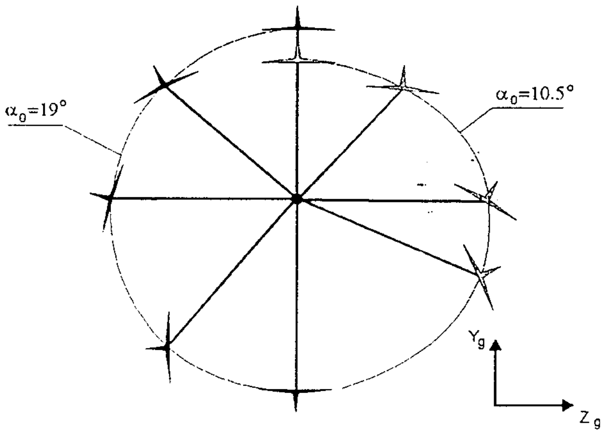


Figure 14 Model equilibrium orientations at different angles of attack (cg at joint position)