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WIND TUNNEL MEASUREMENTS OF SHIP INDUCED TURBULENCE AND THE PREDICTION OF HELICOPTER ROTOR BLADE RESPONSE

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ABSTRACT

An investigation of the flowfield over the flight deck of a Royal Fleet Auxiliary ship has been undertaken. Results were obtained on board a full scale ship and also by using a scale model in a wind tunnel. Mean and time dependant flow properties were measured in both cases. Comparison shows that satisfactory representation of the flowfield can be obtained by undertaking tests at model scale.

A theoretical model has been assembled to predict the blade flapwise deflections when operating on the deck of a ship, during rotor run-up and run-down. The results of the wind tunnel tests have been used as an input to this model and using the Lynx helicopter on an R.F.A. sized ship, the blade motion has been calculated.

Tail cone strikes have not been predicted with a moderate gust but encroachment on fatigue life is predicted.

INTRODUCTION

During the service life of a helicopter it will be necessary to operate in very severe weather conditions including high winds of a gusty nature. Under such circumstances starting or stopping the rotor brings new hazards. With large aerodynamic forces acting on rotor blades and little centrifugal stiffness due to the low rotor speed, large movements can occur (blade sailing). Such movements if large enough can cause damage either by a blade strike on the fuselage or object close to the aircraft or by subjecting the blade to stresses of sufficient magnitude to cause fatigue damage.

This study analyses theoretically the effect of gusts impinging on a rotor spinning at the low speeds associated with acceleration or deceleration of the rotor between rest and normal operating speed. The behaviour of the rotor blade is governed by a combination of the following effects, the influence of each changing with rotor speed:-

1. Centrifugal force due to rotation
2. Aerodynamic forces
3. Dynamic forces (e.g. Coriolis and gyroscopic accelerations)
4. Elastic deformation (including the hub)
5. Gravitational forces
6. Rotor hub motion
7. Pilot's control inputs

At low rotor speed there is little centrifugal stiffening and if there is still air, the aerodynamic forces on the blade possess a similar rate of increase as the centrifugal stiffening and no problem is created. Should, however, a gust occur, the blades are liable to large excursions since the centrifugal stiffening is insufficient to control the aerodynamic forces imposed by the gust. With such large excursions it is possible for a blade to strike either objects on the ground or the fuselage itself. Although the pilot has the ability to control the rotor via collective and cyclic pitch inputs, such control is only effective when the rotor is turning at reasonable speed and whether the pilot can react quickly enough. At normal operating speed, the control is sufficient to position and orientate the rotor disc to avoid a hazardous situation, however with a stopped rotor in still air the control inputs have no effect. This implies that the ability of the pilot to control the rotor through an adverse gust will depend on the rotor speed variation throughout the duration of the gust.

In the case of a blade attachment via a flexible element there is a greater stiffening at low rotor speed compared with a fully articulated blade and less blade deflection can be expected. However, in the case of a fully articulated blade not only is there less stiffening at low rotor speed but there are mechanisms on the rotor hub which restrain the blade motion at low rotor speeds (and also which retract as the rotor speed increases). These devices, namely the droop restrainer and the anti-flap assembly, restrict movements of the flap-wise deflection of a blade and with a large enough excursion, impact with either of the above limit stops can occur. This alters the stiffness drastically and should a divergent behaviour be induced then severe damage will occur either to the blade tip with a fuselage/ground strike or fatigue damage to the rotor hub and blades due to excessive impact loads on the limit stops.

This excessive motion has not been investigated fully and the ultimate aim of this work is to provide an analysis and associated computer program to assess the behaviour of a particular rotor system to any required gust, operating procedure and movement of a ship. Previous work has furnished methods for use on a comparative basis, however this method is intended to provide results on an absolute basis. Such a facility is of increasing importance as helicopters are being required to operate in progressively worse conditions.

The computer programme requires representative information of the flowfield over the flight deck. Suitable theoretical techniques exist for a calculation of many flowfields which are dominated by attached flows. However, in this case where the details of a separated flowfield are required, no satisfactory theoretical model exists. Therefore, the investigation had to be of an experimental nature.

Difficulty is experienced in obtaining flowfield data for specified test conditions on board a full-scale ship in typical operating conditions. Testing at model scale in a wind tunnel provides a cheap and convenient alternative. An additional advantage of testing at model scale is that an investigation of the airflow over the rear of the ship can be undertaken during the initial design stage and thereby allows the solution of any problems at an early stage of development. However, using the model testing technique, many differences are produced in the test conditions from those experienced by a full-scale ship at sea. Typical examples are: free-stream turbulence, Reynolds number and the atmospheric boundary layer. The differences may have a significant effect on the separation points and wake conditions over the flight deck and it is important to compare the wind tunnel results with those obtained at full-scale to ensure that satisfactory simulation is being achieved.

An investigation of the flow conditions over the flight deck of a Rover Class Royal Fleet Auxiliary has been undertaken on board a full-scale ship and also using a scale model mounted in a wind tunnel. Qualitative data were obtained from a flow visualisation study and quantitative data in the form of the three orthogonal velocity components, i.e. fore/aft, lateral and vertical, at several positions over the flight deck at rotor height. Analysis of the velocity components allowed the total velocity and direction to be obtained in addition to the frequency and scale of the local flow turbulence. There was no representation of a helicopter on the flight deck in either series of tests.

FULL-SCALE TESTS

Golf ball anemometers, described in Ref. 1, were used during the experiments carried out on board the full-scale R.F.A. to measure the two local horizontal orthogonal velocity components simultaneously at a point above the flight deck. The diameter of the golf balls was 0.03m. The vertical component was measured using a Gill propellor anemometer. The maximum frequency response of the devices was 4 Hz and they were chosen because of their robust nature and ease of use. They were mounted on a stand which could be moved around the deck, and when in position the anemometers were at a height of 4m above the flight deck. This was within the range of rotor heights of operational helicopters, e.g. Sea King and Lynx. Data were obtained at the positions shown in Fig. 4 for several relative wind directions. An anemometer and vane were used to monitor the relative wind speed and direction. The outputs from the devices were recorded simultaneously for three minutes. The tests were undertaken with relative wind velocities in the range of 15-30 knots (7.5-15.5m/sec). All the local wind velocities were normalised by the relative wind velocity to allow for changes in test conditions during the test programme.

MODEL TESTS

The model testing phase of the experimental investigation was carried out in the University of Southampton 2.1m x 1.7m wind tunnel using a 1/120th scale waterline model of the Rover Class R.F.A. The constraints of the wind tunnel walls had negligible effect on the airflow over a model of this size. All important items of the ship's superstructure were represented in the geometry of the model. It was mounted on a ground board, positioned at approximately mid-height of the working section and could be rotated to produce any angle of wind direction. A flap was positioned at the trailing edge of the board to remove any circulation around it which was produced by the model.

The presence of the ship and its superstructure has a large effect on the flow over the rear of the ship. It is important to determine the magnitude of this effect and its dependence on wind direction. For this reason, a flow visualisation study was undertaken in the wind tunnel to allow a qualitative examination of the flowfield over the flight deck.

The flow visualisation study employed a single smoke probe which could be moved to any position around the ship. Care was taken to ensure that the smoke probe and stand did not interfere with the flow over the ship.

Following the flow visualisation study the second phase of the wind tunnel programme was undertaken. This involved using a three axis hot wire anemometer to obtain the local flow velocity and direction at several points over the flight deck. This type of measuring device was chosen because of its compact size and also the need to measure the three orthogonal velocity components simultaneously. It was mounted on a traversing rig which was attached to the ground board downstream of the model. The data were obtained for the same test cases as in the full-scale tests. The anemometer was positioned at the correct scaled height above the deck and was aligned into the local mean flow direction in order to ensure that the flow always approached the anemometer from a direction within the cone of acceptance. Tests were undertaken in the reduction software to ensure that this condition was met. The three outputs from the anemometer were recorded for a period of 1 minute.

The working section velocity was measured using an upstream pitot static tube and the tests were carried out at a free-stream velocity of 35 knots (18m/sec). The free-stream turbulence level in the working section was 0.4%.

FLOW VISUALISATION

The flow visualisation photographs shown in Figs. 1-3 demonstrate the two principal types of flowfield over the flight deck. In Fig. 1 the smoke probe was positioned on the ship's longitudinal centre line and the wind was from the ahead direction. It clearly exhibits the highly turbulent superstructure wake flow which covered the whole of the flight deck.

Figs. 2 and 3 were obtained with the model positioned to produce a relative wind direction of Red 135 (135° to Port). The smoke can be seen in Fig. 2 to rise over the side of the ship resulting in an upwash in the region of the windward edge of the deck. The flow passed over the deck in an approximately free stream direction, and in Fig. 3 the presence of the downstream superstructure can be seen to cause the flow to travel laterally across the deck. The superstructure wake on the lee side of the ship is also shown. In this latter case, the superstructure did not produce any major flow separation over the flight deck but it produced a large change in local flow direction. Therefore, even when the flow approaches the ship from the stern, the superstructure still has a large effect on the flow-field over the flight deck.

DISCUSSION OF RESULTS

The voltage outputs of the anemometers in both the full-scale and model-scale tests were analysed by using a computer which sampled the channels of recorded data simultaneously and allowed the mean and time dependent characteristics of the flow to be determined. Typical properties obtained were mean, maximum and minimum velocities, standard deviations of the results and power spectral densities.

Two flowfields, dependent on wind direction existed over the flight deck, as observed in the flow visualisation study. The highly turbulent wake of the superstructure and the relatively unaffected free-stream air flow. The quantitative results presented are those obtained when the wind direction was from 20° to starboard. This wind direction produced both the flowfields and therefore allowed an examination of the characteristics of them both, point 4 in the wake flow and point 2 in the "free-stream" flow.

FULL-SCALE

The mean total velocities recorded at points 2 and 4 when the wind direction was Green 20 (20° to Starboard) were $1.53V_\infty$ and $0.85V_\infty$ respectively. This discrepancy in velocity was one of the major differences between the two basic flight deck flowfields. The three components of the velocity at each point will now be discussed.

The majority of the difference between the velocities arose from the reduced fore/aft component recorded at point 4. The largely unaffected flow at point 2 had a typical velocity of

$1.4V_\infty$ whilst that at point 4 had been reduced to an average of $0.6V_\infty$ due to the presence of the superstructure wake.

The lateral velocity components were of the same magnitude at the two points, however, their directions were opposite. The velocity at point 2 was in a starboard to port direction and vice versa for point 4. The change in direction recorded at point 2 was due to the swirl of the superstructure wake flow.

The vertical velocity components at point 2 clearly showed the upwash produced as the wind passed over the bluff windward side of the ship. An upward vertical velocity of typically $0.20V_\infty$ was recorded. The presence of the deck produced a nominally zero vertical velocity component at point 4.

MODEL SCALE

The mean local velocities (U_L/U_∞) were 1.47 and 0.62 for points 2 and 4 respectively.

The power spectral densities are shown in Fig. 5. The increased turbulence in the wake of the model at point 4 is also shown. These show that the frequency of the ship induced turbulence measured in the wind tunnel was much higher than that produced by the full-scale ship. This was to be expected because of the small scale of turbulence produced by the model.

COMPARISON OF FULL-SCALE AND MODEL SCALE RESULTS

The magnitude of the full-scale and model scale mean local velocities discussed earlier show good agreement, as shown in Fig. 6. The direction of the local flow also displayed satisfactory agreement. This demonstrated that although there were differences in test conditons, e.g. free-stream turbulence and Reynolds number effects, satisfactory representation of high mean characteristics of the flight deck flowfield was obtained during the model scale tests.

The frequency of the turbulence produced over the flight deck at model scale was much higher than that recorded at full-scale. The size of the ship and frequency of turbulence generated are related by the Strouhal number, i.e.

$$Strouhal\,number = \frac{Vf}{\ell}$$

where V is velocity

f is frequency of turbulence

ℓ is a characteristic length of the ship.

To investigate the Strouhal number dependence of the results, the frequency scale of the full-scale power spectral densities were scaled by the ratio of full-scale to model scale Strouhal numbers. The result is that the two distributions show satisfactory agreement, as shown in Fig. 7. The peaks occur at similar frequencies, however the full-scale results reduce in magnitude more rapidly than the model results. The probable reason for this is the poor frequency response of the anemometers used during the full-scale tests.

CONCLUSIONS

Comparison of the full-scale and model scale results demonstrate that satisfactory flight deck flowfield information can be obtained at model scale. This allows data for the prediction of blade motion to be obtained in the wind tunnel and saves the expensive and difficult requirement of obtaining results on board ship.

DISCUSSION OF THE THEORETICAL METHOD

The theoretical model presented here makes the following assumptions:-

- Flapwise freedom only
- Use of mode shapes for specifying blade response
- Static aerofoil characteristics
- Idealised rotor run up and run down laws
- No induced velocity
- No aerodynamic interference from the fuselage

Using a set of orthogonal mode shapes the equations of motion obtained are

BLADE RESPONSE

$$z(r,t) = \zeta_i(t)\, g_i(r)$$

EQUATION OF MOTION

$$I_n \ddot{\zeta}_n + \rho_n^2 I_n \zeta_n + (\Omega^2 - \Omega_N^2) C_{mn} \zeta_m = F_n$$

$$where\ I_n = \int_o^R Mg_n^2\, dn \ (\ the\ modal\ inertia\ )$$

$$C_{mn} = \int_o^R T g_m' g_n'\, dr$$

$$T = \int_r^R M\eta\, d\eta$$

$$F_n = \int_o^R Lg_n dr - \int_o^R Gg_n dr \ (\ the\ external\ forcing\ to\ the\ nth\ mode.\ (lift\ minus\ the\ gravity\ terms))$$

The flapwise deflection of the blade is assumed to be a degenerate function where the spanwise variation is expressed via the mode shapes g_i (with modal frequency ρ_i) and the timewise response of each mode ζ_i. The dashes denote the spanwise derivative, the dots denote the timewise derivative.

M is the mass distribution

L is the lift distribution

G is the gravitational acceleration

The C_{mn} terms occur because the modes are appropriate to only one particular rotor speed (Ω_N) and the analysis is required at all speeds. These terms vanish at $\Omega = \Omega_N$ at which speed the modes apply, however the behaviour of the rotor is required at low rotor speeds especially when the effect of these terms are required to be the most accurate. Because of this C_{mn} terms are evaluated by the modal program (where a very precise integration is performed) and read into the blade sailing program, rather than being calculated by a less stringent method.

The above equations of motion are integrated numerically by 4th order Runge-Kutta (Ref. 5). Numerical solution was elected since complete freedom to specify gust characteristics, rotor speed variation, and ship motion is required.

ROTOR ACCELERATION LAW

A rotor run up law was used which assumes a constant torque from the powerplant, and that the rotor drag torque varies with the square of the rotor speed. Under these assumptions the rotor speed variation, during acceleration, is of hyperbolic tangent form. The factors are adjusted to give a specified rotor acceleration time.

ROTOR DECELERATION LAW

The rotor speed variation during a run down has used the same assumptions as the run up law, namely a constant torque supplied by the brake and an aerodynamic drag torque on the rotor which varies with the square of the rotor speed.

The variation is defined by the initial rotor speed, the rotor speed at which the brake is applied, the time at which the brake is applied, and the further time to stop the rotor.

AERODYNAMIC MODEL

A detailed discussion of the aerodynamic model can be found in reference 6. The method is a rationalisation of a separated flow model developed by Kirchoff (see Ref. 7). He investigates the effect of trailing edge separation on the aerodynamic characteristics of an aerofoil section.

Stall of the aerofoil is defined as when the separation point is located at the 70% chordwise station (relative to the leading edge) . The separation point at any incidence is calculated and from this the lift coefficient. Reference 6 compares the model predictions with aerofoil test data and the agreement is very good.

RESULTS

The computer program has been used to assess the rotor behaviour during a run up or run down operation of a Westland Lynx when the ships deck is both stationary and rolling. The wind profile was selected from a combination of reference 8 and the initial results produced by the wind tunnel tests.

Reference 8 show the maximum wind speed for starting and stopping the Lynx rotor as 50 knots. Examination of the tunnel test data shows that passage of the wind over the ship causes a vertical component at the rotor with differing sign either side of the centreline of the rotor disc (this confirms the observations of the smoke tests conducted earlier). For this initial appraisal a vertical velocity of ± 10 knots was assumed. The wind is a combination of the horizontal component of 50 kts and the vertical component of 10 kts being downward on the starboard half of the disc and an upward on the port half. The ship was assumed to have a roll amplitude of 7.5° with a period of 10 seconds. The rotor height was taken to be 30 feet above the roll centre.

The ship motion is applied to the aerodynamic forcing terms only. The wind data is resolved into the disc axes by the current ship roll position. The sideways velocity induced by the deck velocity due to the ship movement is then included. It should be noted that the ship roll rates are very much smaller in magnitude than the rotor speed and so ignoring the effect of ship roll on the rotor dynamic terms is not considered to be unreasonable.

The choice of collective pitch is 4°. It is approximately midway between the minimum and subminimum collective pitch settings for the Lynx. There was zero cyclic pitch input and the other rotor data is

Linear blade thrust 8°

Rotor radius 21 ft

Blade chord 15½ inches

and I.S.A. Sea Level atmospheric conditions.

The aerofoil section data is that of the NACA 0012, which was the only one available at the time. The Lynx blade has in fact a tapering aerofoil section based on NPL 9615. The principal differences of these two aerofoils are felt at higher mach numbers, and as the behaviour to low rotor speed is under study the differences are not considered significant. The difference in zero lift angles are assumed to be absorbed by the control angles. The rotor operation timing used is as follows:-

<u>Run Up</u>

Run up time 10 seconds

<u>Run Down</u>

Time from engine shut down to brake application 17 secs.

Time from brake application to rotor stopped 8 secs.

Rotor brake applied at 47% NR.

The above figures were obtained from stop watch timing on an actual aircraft.

Observation of figure 8 shows that during a run up a downward tip deflection of 50 inches can be obtained (within a rotor speed range of 4%-14%NR).

Figure 9 shows that during a run down larger tip deflections of 55 inches occur (at rotor speeds of 4%-14%NR). (The deflection increases to about 60 inches if the ship roll phasing is altered).

For a tail strike a downward tip deflection of 75 inches is required, this is not achieved with the specified ship and wind conditions used to produce figures 8 and 9. However other computer analysis where the wind components are 60 kts and ± 15 kts and the ship roll amplitude is increased to15° shows that these deflections are possible.

The tip deflections required to cause fatigue damage, however, are dependent on rotor speed, so strictly an examination of the entire blade motion will be required. In order to gain an insight into whether fatigue is being induced, an examination of the 50% NR rotor speed region is shown.

A rotor speed of 50% NR occurs at 1.2 secs after start up (run up) or 15 secs after engine shut down (run down). A tip deflection of the order of 35 inches is required to induce fatigue. The run up cases show no such deflection, but the run down cases fig. 9 show that the fatigue condition is just avoided with a stationary ships deck but ship motion does deflect the blade past the fatigue limit.

CONCLUSIONS

A single degree of freedom theoretical model has been set up to predict the blade motion during rotor run up and down operations on board a ship. It has been used on the Westland Lynx to analyse the effect of gusts on such events.

Data was taken from wind tunnel results for the gusts, aircraft measurements for the rotor speed variation and typical ship roll characteristics for an R.F.A. size of ship.

The theoretical study indicates that the blade fatigue endurance limit can be exceeded with a strong gust (50 kts) and moderate ship rolling ($7\frac{1}{2}$°), whilst a severe gust (60 kts) and large ship rolling (15°) could induce sufficient blade motion to cause a tail boom contact. This latter case exceeds the Lynx design envelope. Experimental validation of the theoretical model has not yet been obtained.

ACKNOWLEDGEMENTS

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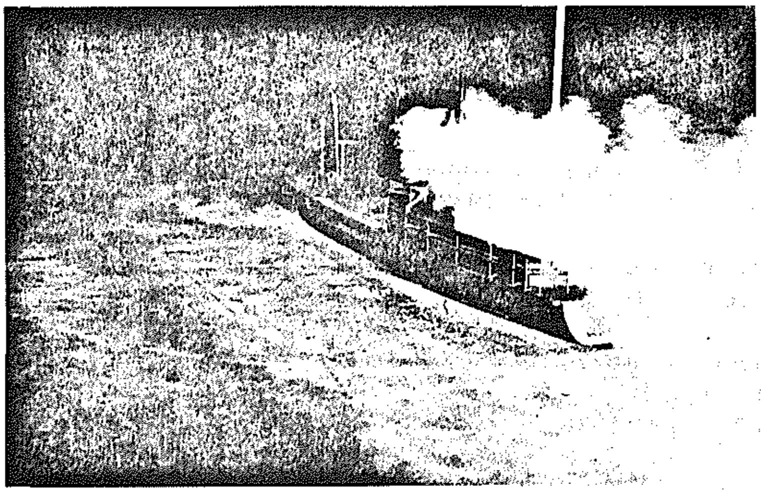


Figure 1 FLOW VISUALIZATION OVER WIND TUNNEL MODEL - STRAIGHT AHEAD.

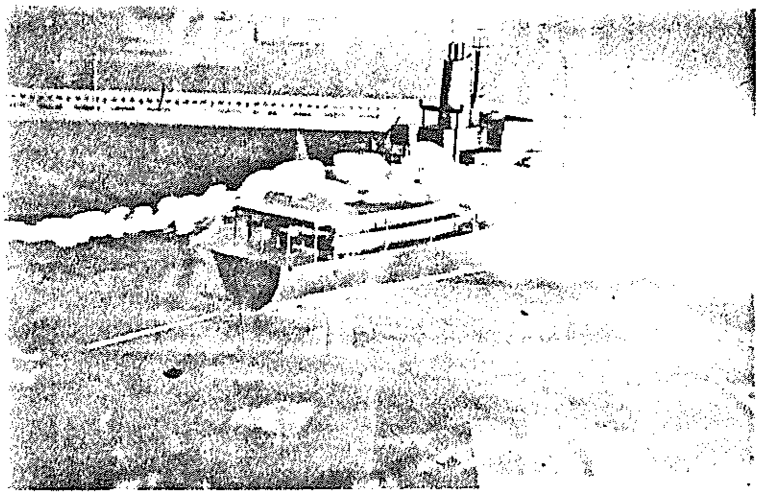


Figure 2 FLOW VISUALIZATION OVER WIND TUNNEL MODEL - 135° TO STARBOARD.

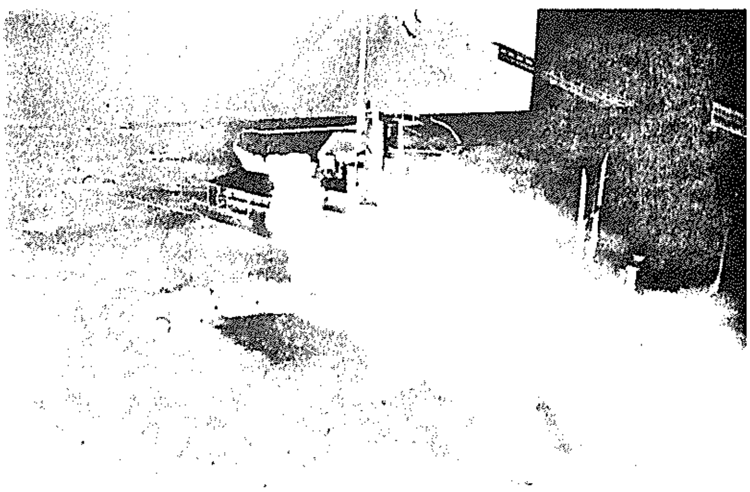


Figure 3 FLOW VISUALIZATION OVER WIND TUNNEL MODEL - 135° TO STARBOARD.

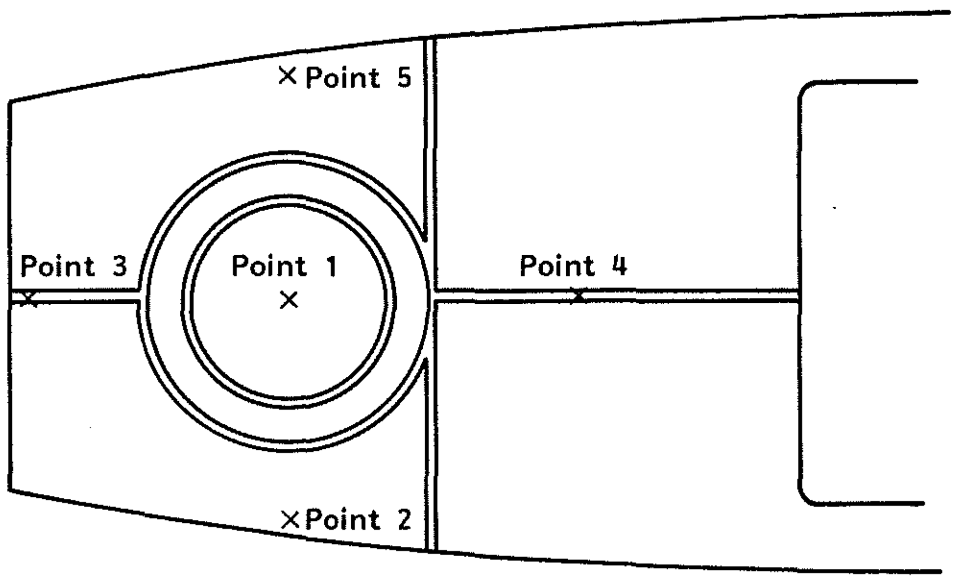


Figure 4 MEASUREMENT POINTS ON FLIGHT DECK

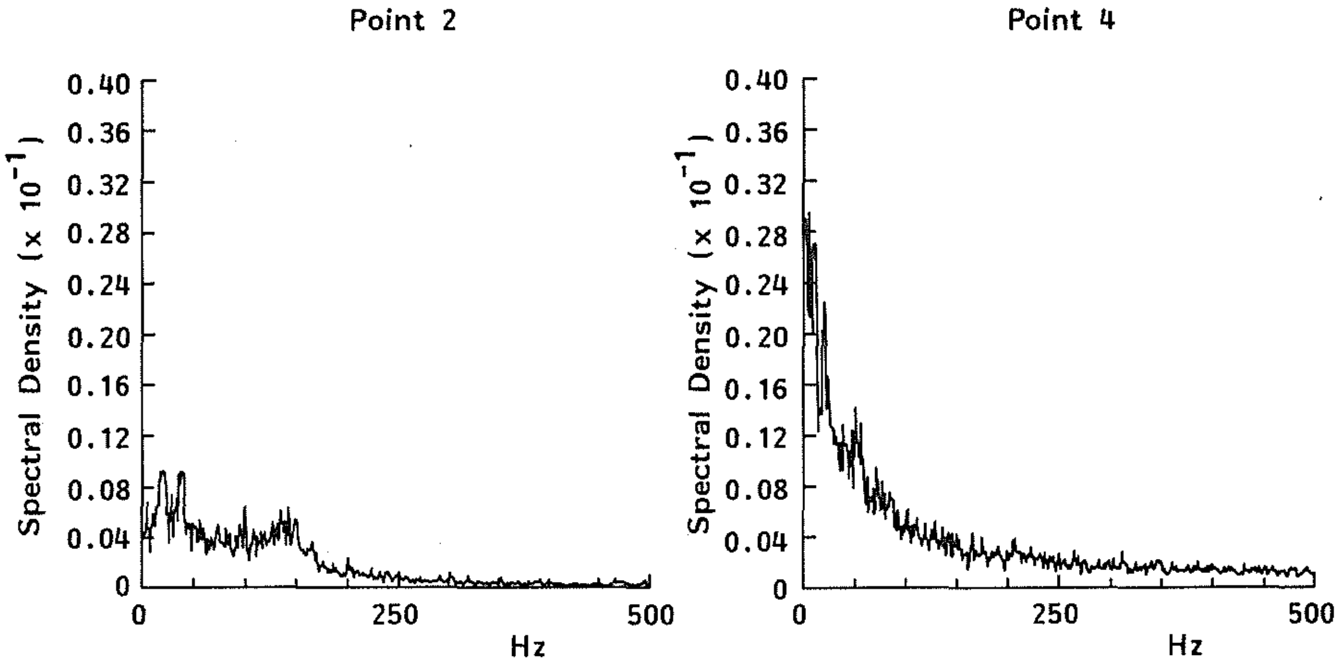


Figure 5 POWER SPECTRAL DENSITIES MODEL TESTS

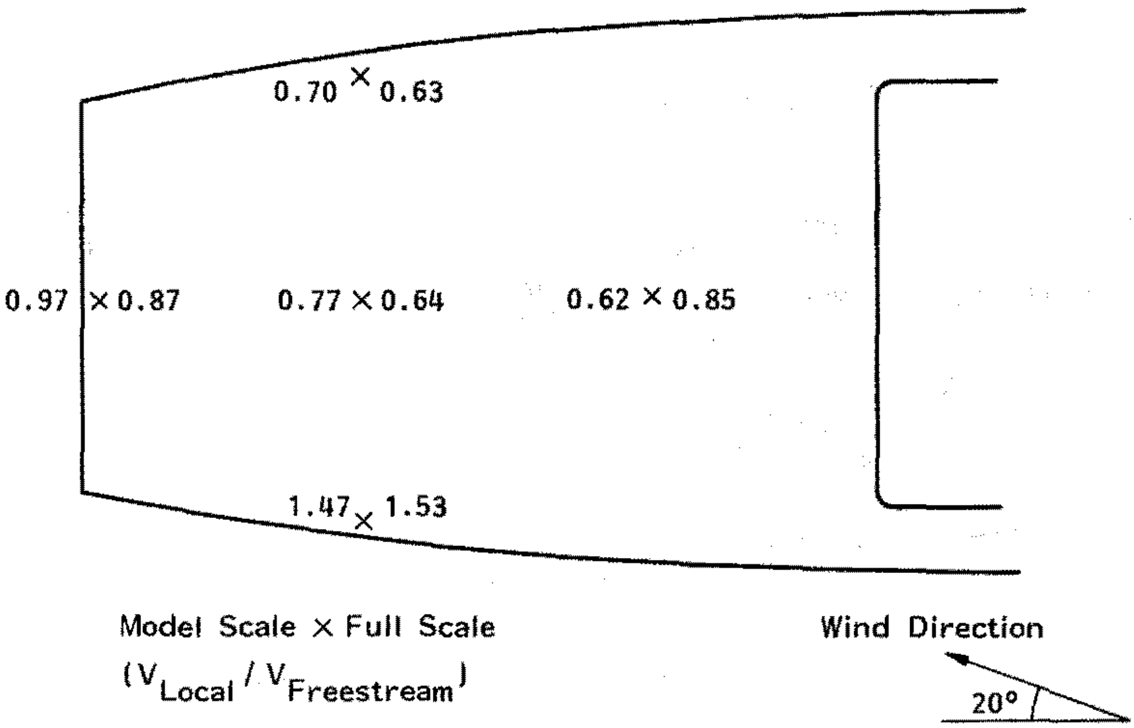


Figure 6 COMPARISON OF MODEL AND FULL SCALE VELOCITIES

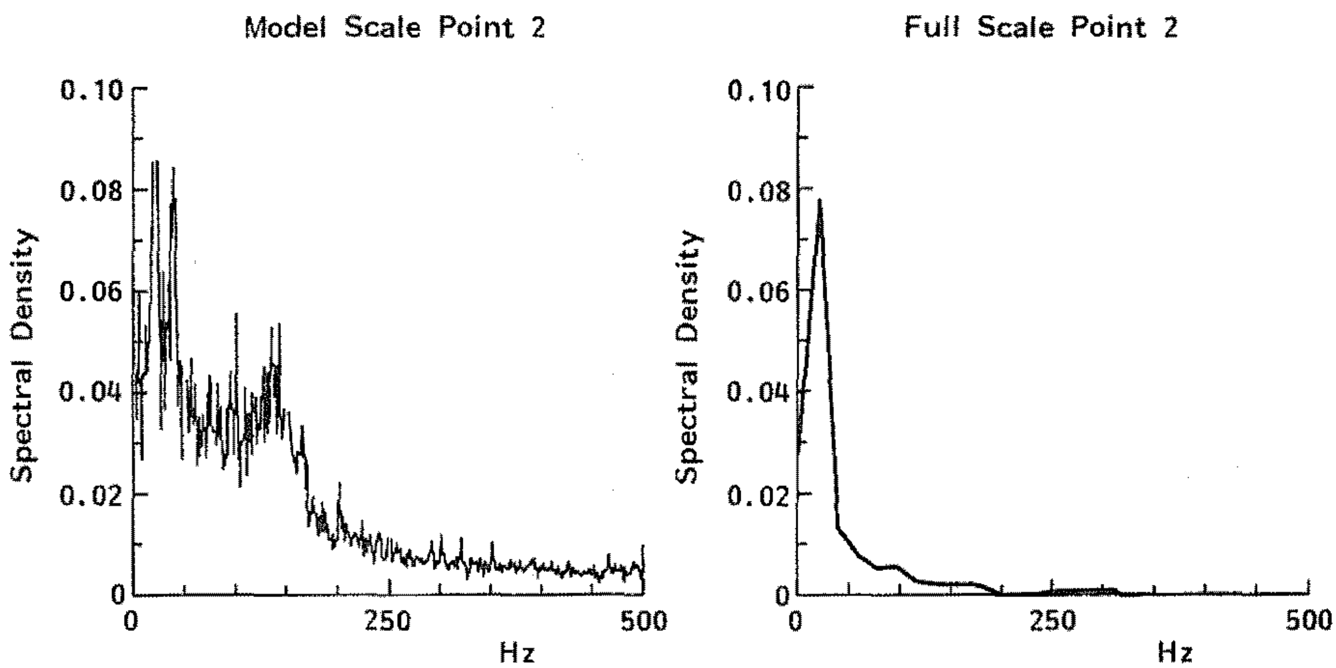
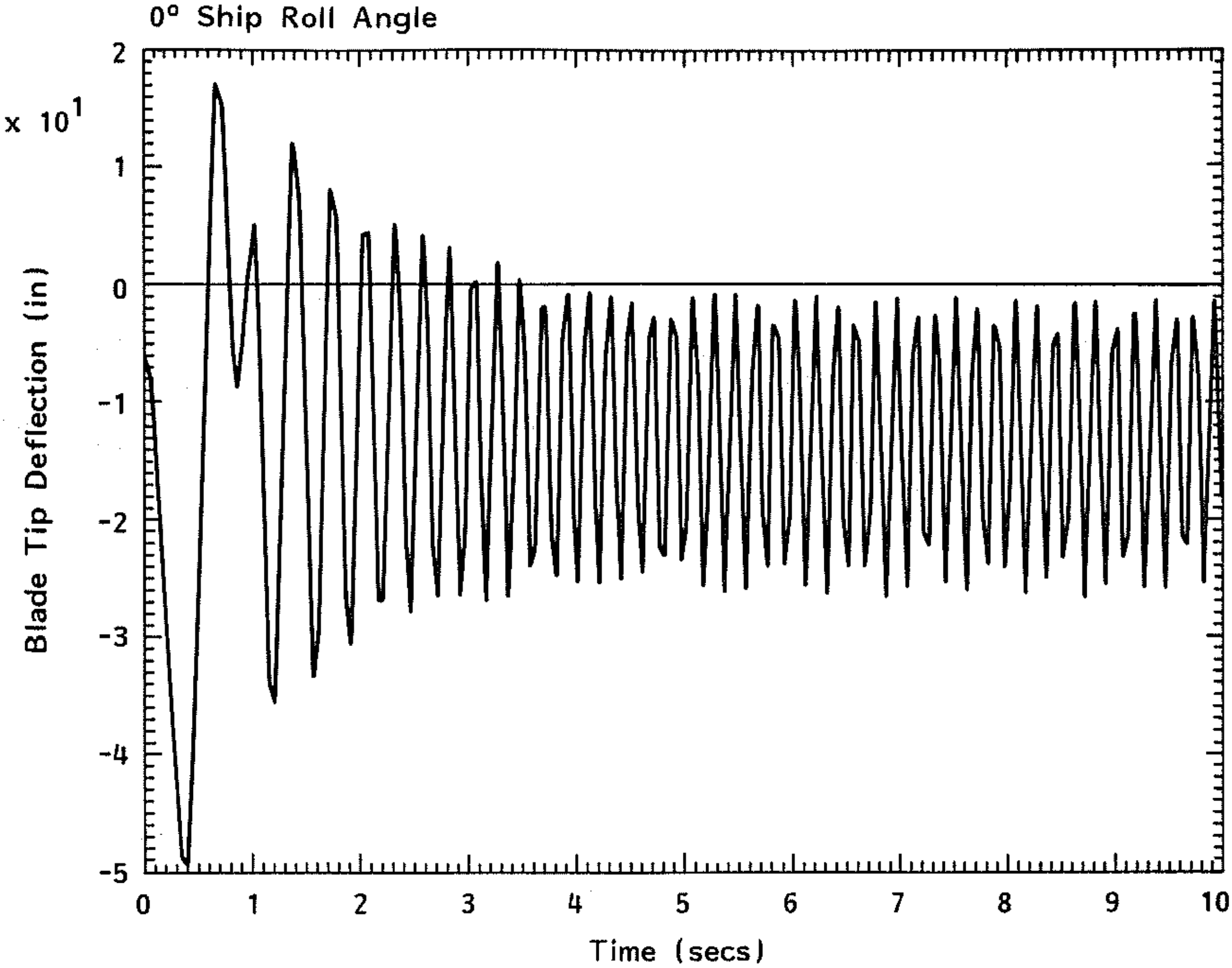


Figure 7 COMPARISON OF FULL SCALE AND MODEL SCALE POWER SPECTRAL DENSITIES.



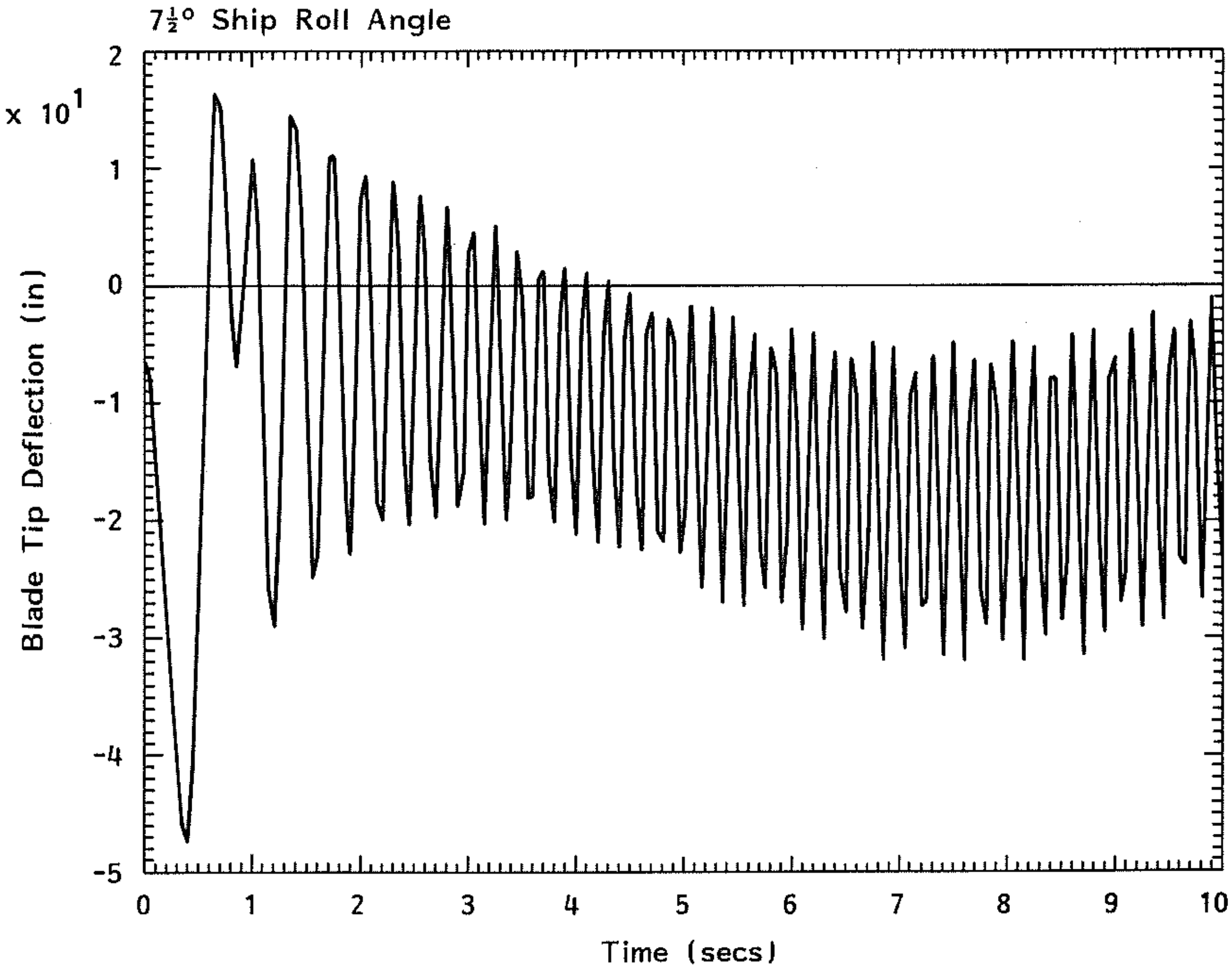
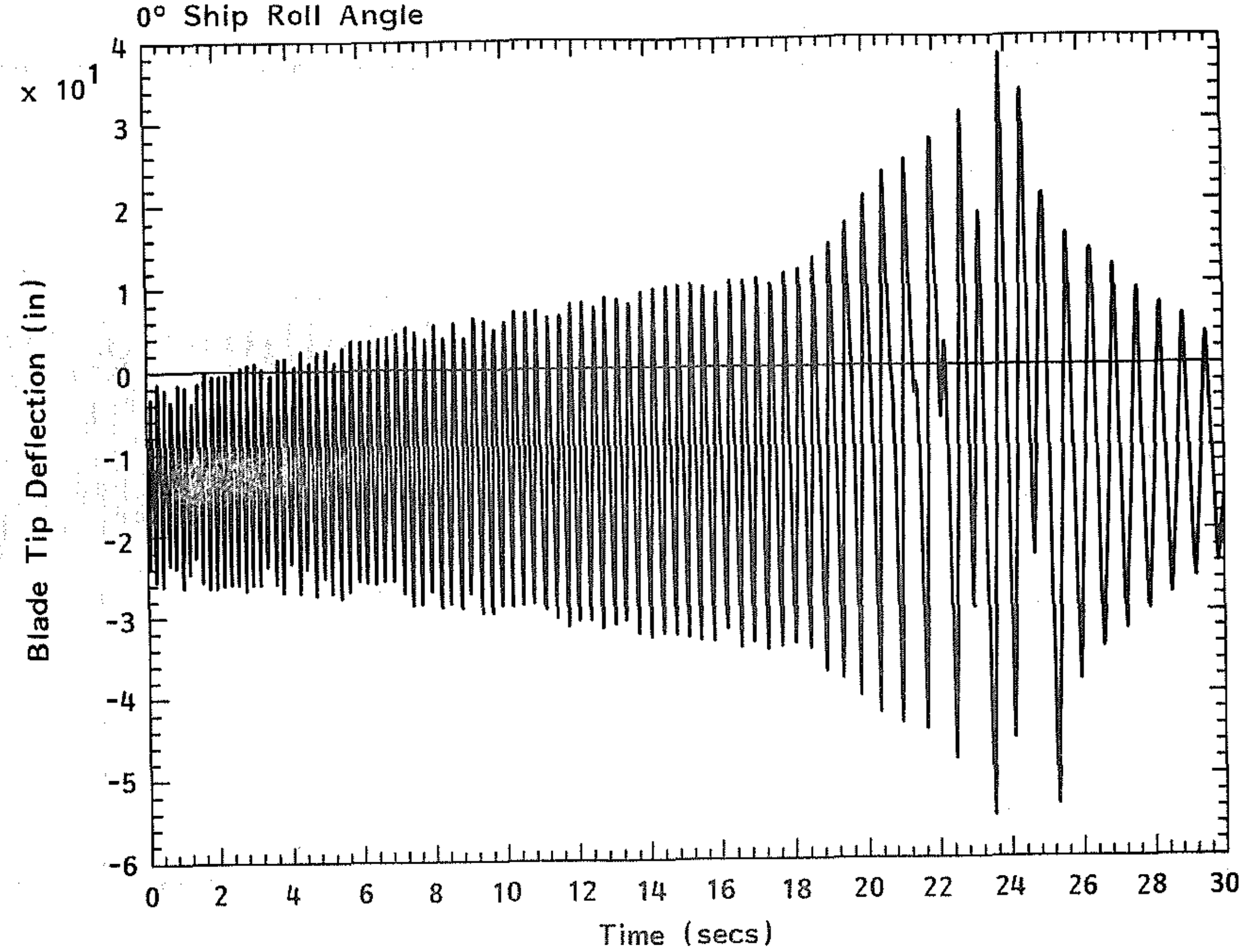


Figure 8 LYNX - RUN UP



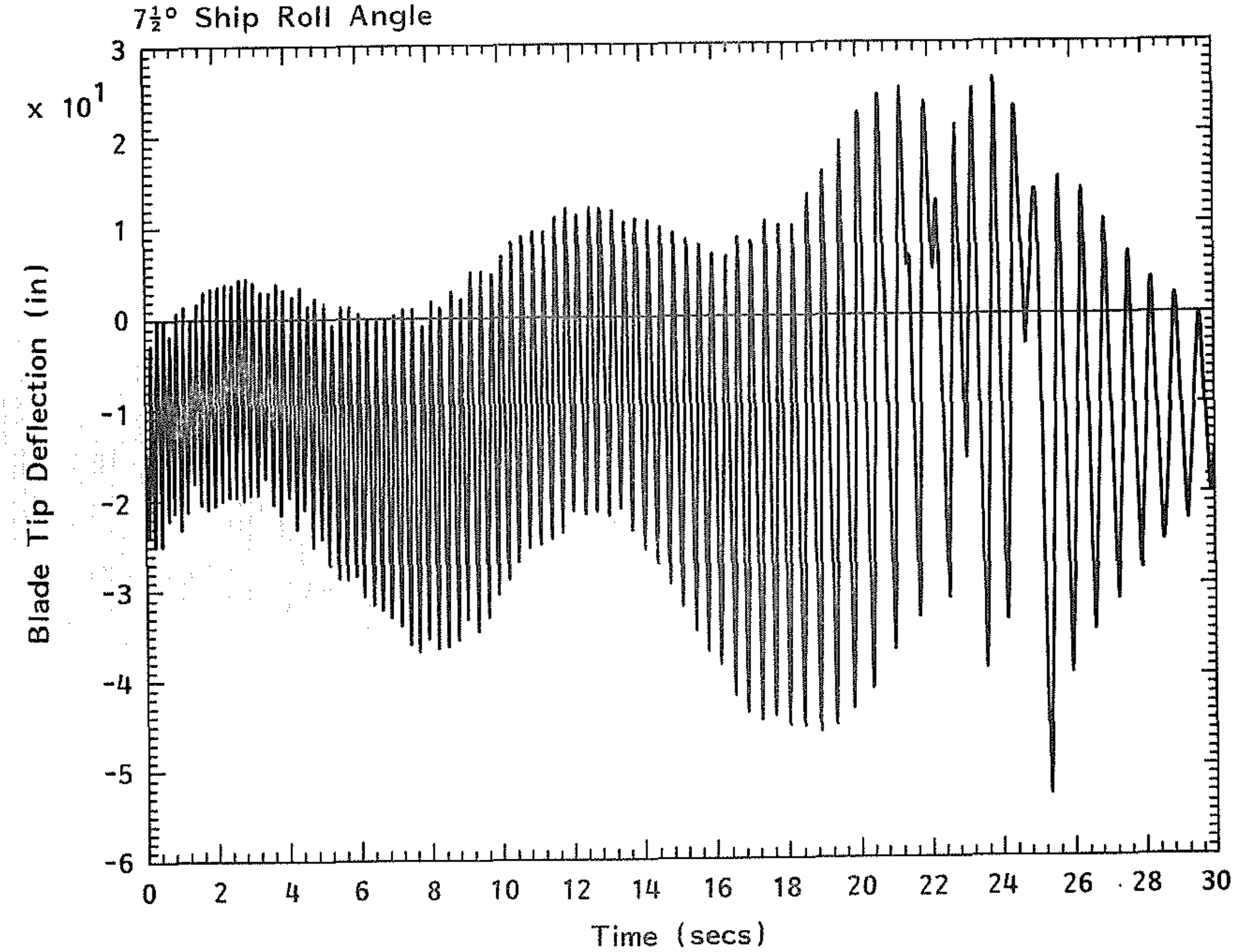


Figure 9 LYNX - RUN DOWN