Modelling the Transient Response of the Dines Anemometer

Jeffrey D. Kepert

Centre for Australian Weather and Climate Research, Bureau of Meteorology, 700 Collins St, Melbourne Vic 3000.

J.Kepert@bom.gov.au

1 INTRODUCTION

The Dines, or pressure-tube, anemometer, consists of a large-diameter pitot tube mounted on a vane, connected to a unique manometer. This manometer consists of an open-bottomed tapered float in a water tank, with the pressure tube from the pitot head feeding into the air space in the float. As the wind speed rises, the pressure inside the float increases and the float rises, moving the recording pen. Further information on the instrument may be found in [1] and [2]. The Dines anemometer is now obsolete in Australia, having been largely replaced by cup anemometers. Nevertheless, historical records from the instrument are important to understanding the wind hazard climatology, not least since two of the strongest gusts ever recorded on the Australian mainland, in Tropical Cyclones Tracy of 1974 and Vance of 1999, were recorded on Dines instruments.

The behaviour of cup anemometers in turbulence has been extensively studied, but comparatively little similar work has been done on the Dines, and this has mostly focussed on the mean, rather than the transient, response. Here, we present results from a newly developed physical model of the transient response of the Dines anemometer. Two previously observed resonances are confirmed, and their physical mechanism described. A third low-frequency oscillation, not previously known, is found in the model and it is shown that the instrument may overspeed, albeit for different reasons to cup anemometers.

2 MODELLING THE FLOAT CHAMBER

The manometer of the Dines anemometer as illustrated in Fig. 1 has a complicated geometry, designed to produce a steady-state float displacement that is linear in the applied wind speed. This geometry complicates the analysis, so for convenience a simpler geometry will here be assumed: (i) The cross-sectional areas of the water inside and outside of the float are equal; (ii) The float and containing vessel have parallel sides; (iii) The pressure in the suction chamber is constant, or equivalently, the suction chamber is open to the atmosphere; (iv) The movement of the float and liquid experience Newtonian damping with time-scales _1 and _2 respectively; and (v) The relative motion of the float and liquid is Newtonian damped with time-scale _3, to represent the choke at the bottom of the float (see Section 2.2). The float chamber is then nearly equivalent to a U-tube manometer with a frictionless piston supported by some trapped air in one arm, and forced by varying the amount of trapped air. Figure 1 sketches the successive approximations, from tapered float, to parallel-sided float, to U-tube. In the U-tube, the piston represents the Dines float, and the manometer liquid by the water in the Dines float chamber. The trapped air between the piston and the manometer liquid corresponds to that inside the Dines float, and acts as a spring between the two masses.

The variables in the system are the positions and velocities of the piston and manometer liquid and the pressure of the trapped air. The independent variables are the piston mass, the tube area, the amount of trapped air, the pressure of air in the suction chamber, and the mass of the liquid. The equations governing the system are given by [3]. Linear analytic solutions and numerical solutions (by fourth-order Runge-Kutta integration) were obtained.

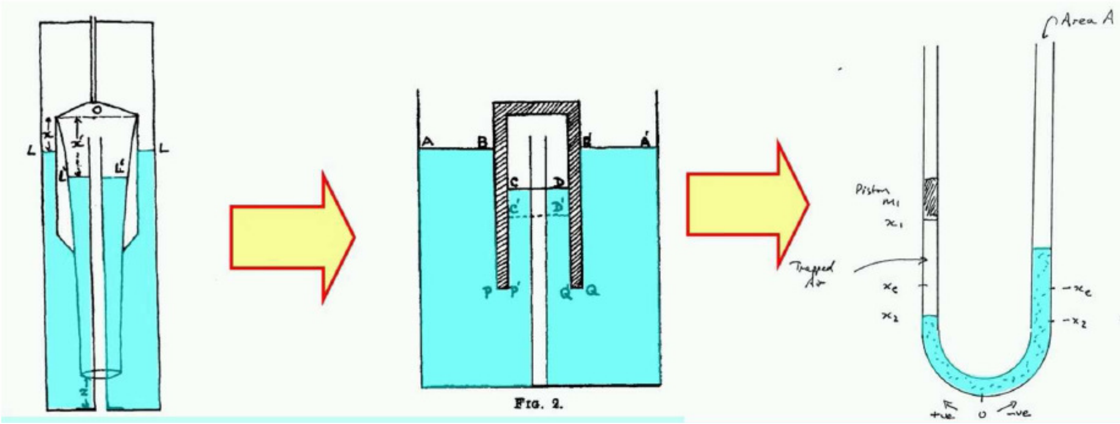

Figure 1: The Dines anemometer float chamber and successive approximations. The left panel shows the classic Dines manometer, with the float of tapered cross-section designed to produce a displacement that is linear in wind speed. The central tube feeds the pressure at the pitot tube entry into the interior of the float. Blue shading represents water. The middle panel approximates the float as having parallel sides. The right panel has similar topology to the other panels, but approximates the liquid as moving as a single mass in a U-tube. The float is represented as a piston in one arm of the tube, supported above the liquid by the trapped air. The notation is that x1 represents the position of the piston, x2 the position of the liquid top in the piston arm, and xe the equilibrium position that the liquid would take if the piston was removed. Distances are measured from the bottom of the U-tube, with the piston arm being positive. The left and centre drawings are from [2].

2.1 Undamped behaviour

Kepert [3] considers coupled sinusoidal oscillations of the system, and shows that there are two natural frequencies. Expressions are given for the frequencies and relative amplitudes of the float and water. The lower frequency oscillation has the liquid and piston in phase, while the higher frequency one has them in opposite phase.

A time-series plot of simulated motion for the full equations is shown in Figure 2. This example clearly shows periods where the liquid and piston oscillate in phase (e.g. 690 – 770), and periods where they are out-of-phase. Apparently both oscillations are present and beating is occurring; see further discussion of this case below. The mean position of the float (black line) is significantly displaced from its equilibrium position x1e (lighter blue line). In the usual anemometer parlance, the instrument is overspeeding; that is, the measured mean wind speed has a positive bias. In contrast, the mean liquid position is indistinguishable from x2e (light green line).

The power spectra of float and water position for this simulation are shown in Figure 3, with the frequencies from the linear analysis, !1 and !2, indicated by the filled diamonds. The spectrum is dominated by broad peaks around $\acute{\omega}_1 \approx 0.6037$, $\acute{\omega}_2 \approx 1.2347$, and the harmonics thereof. The nonlinearity is evident from the relatively large amplitudes of the harmonics, and from the broadness of the peaks. Reducing the amplitude of the oscillations by changing the initial condition leads to narrower spectral peaks and fewer spikes, confirming the role of nonlinearity. There is significant power in the motion of the piston, but not the liquid, at frequencies below 0.3, while the power is more similar for other peaks in the spectrum.

We now consider the cause of the overspeeding. Figure 4 shows a longer version of Figure 2, including also the low-pass filtered float position, which is a maximum when the water and piston are most obviously out-of-phase, and a minimum when they are in-phase. The trapped air acts as a nonlinear spring – the force required for a given incremental displacement is larger when the air

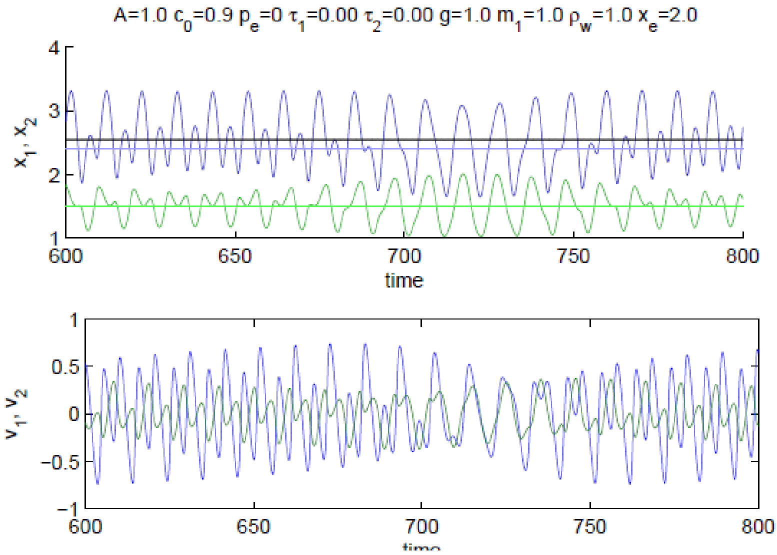

Figure 2: Time series of simulated Dines manometer. The upper panel shows the float (blue) and liquid (green) position, and the lower panel shows the respective velocities. The lighter lines in the upper panel show the equilibrium(i.e. zero-motion) positions of the float and liquid, and the black line shows the mean position of the float (calculated over a much longer period than that shown here).

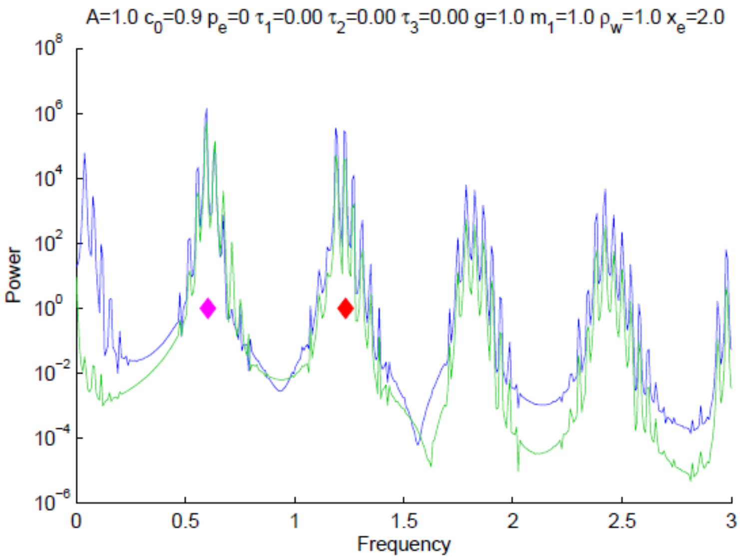

Figure 3: Power spectra of float (blue curve) and water (green curve) positions from the simulation in Figure 2. The diamonds indicate the frequencies for the coupled oscillation from the linear analysis.

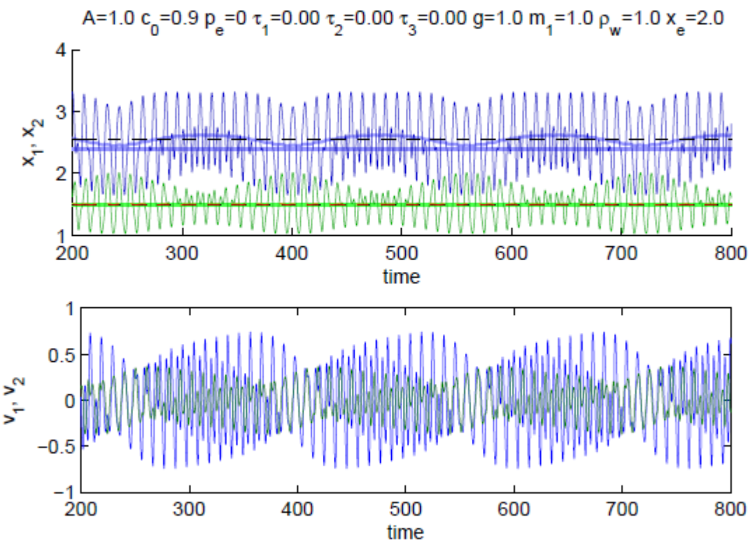

Figure 4: As in Figure 2, except for a longer period. The thick lighter blue curve shows the low-pass filtered piston positions. The similar green curve is indistinguishable from the water mean position.

Figure 5: Photograph of the lower end of a Dines anemometer float, showing the choke. The pressure tube enters up the hole in the middle, almost filling it.

is already compressed from its equilibrium position, than when it is rarefied. Thus, as the amplitude of the out-of-phase oscillation increases, the piston will experience a nonlinear increase in the upwards force it experiences at the bottom of its cycle, when the water rises to meet it. This appears sufficient to increase its mean position over that that would occur with a smaller-amplitude, more linear, oscillation.

2.2 Damping the relative motion

In a real Dines anemometer, the bottom of the float is not open, but contains a constriction, shown in Figure 5. We have not been able to discover any literature on this feature, and so the reasons for its inclusion in the design are unclear. However, it will clearly have a damping effect on the relative motions of the float and the liquid, and was the motivation for the inclusion of the damping of the relative motion in the equations of motion.

Figure 6 presents plots summarising the response of the model to sinusoidal forcing of various frequencies, with $\tau_3 \neq 0$. It is clear that the out-of-phase (i.e., higher frequency) resonance is weaker than the in-phase (lower frequency) with these settings, as is physically reasonable. In the late 1960’s, Borges [4] conducted laboratory experiments with a pressure-tube anemometer float chamber, in which sinusoidal pressure forcing was applied. He presented a graph showing the amplitude and phase of the float response, reproduced here as Figure 7. Clearly, this figure is in good agreement with Figure 6(b, c). Note that [4] presents results for several different mean wind speeds. Variation in the mean wind speed changes the mean mass of trapped air, and hence the resonant frequencies. The results of Borges suggest that the magnitude of the out-of-phase resonance is wind-speed dependent, consistent with other simulations with the model, but full investigation of this phenomenon in the model awaits further investigation.

3 DISCUSSION

A simplified model of the Dines anemometer has been developed. Solution of the linearised equations reveal two fundamental frequencies, corresponding to oscillations in which the water and float are either exactly in or exactly out of phase. The former oscillation has the lower frequency. Numerical solutions reveal that the linear solution well captures the dominant frequencies, and that the numerical solutions contain additionally a rich array of harmonics and interharmonics of the linear frequencies. Nonlinearity in the out-of-phase oscillation leads to a positive bias in the mean measurement (overspeeding), the magnitude of which depends on the

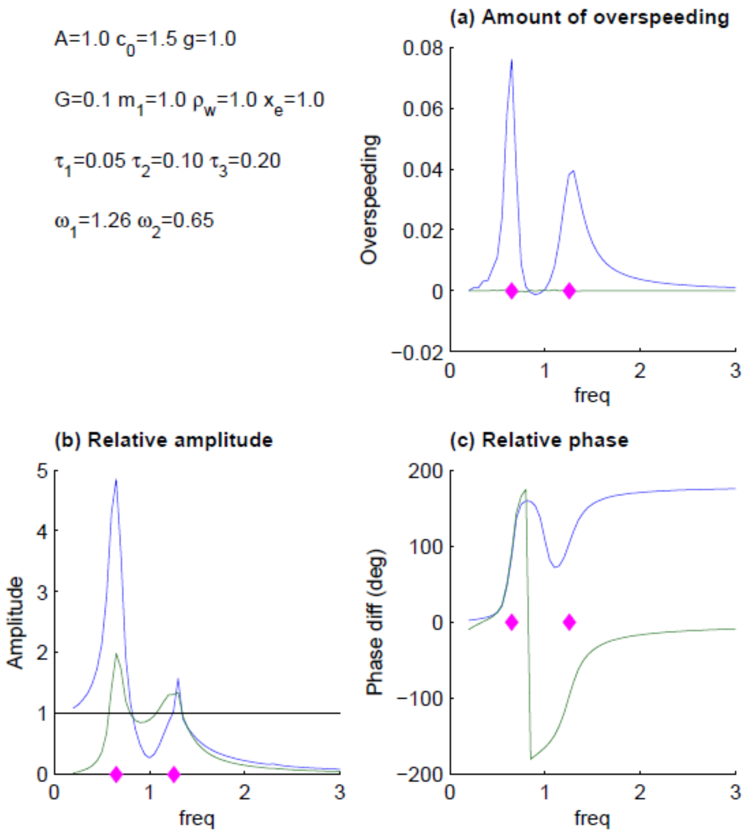

Figure 6: A summary of the behaviour for the forced damped system. Each panel shows the system behaviour as a function of forcing frequency, with the natural frequencies indicated by magenta diamonds. Parameters are shown at top left, notation as in [3]. (a): the mean piston and water position, relative to that expected for steady forcing. (b): the amplitude of the piston and water oscillations, normalised by the expected piston amplitude from the calibration equations. (c): the phase difference between the forcing and the response.

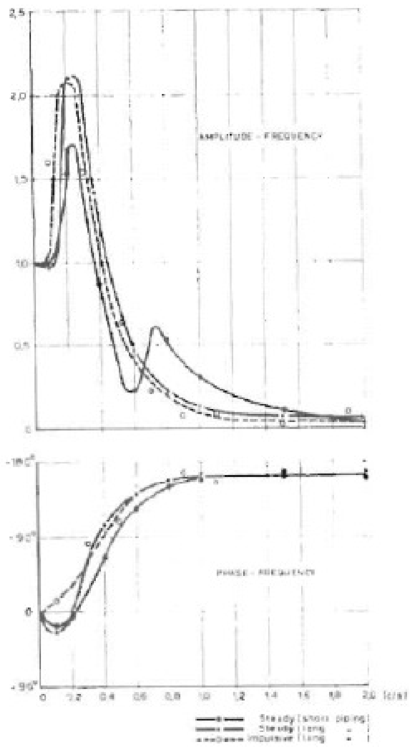

Figure 7: The relative amplitude (top) and phase (bottom) of the float movement, as a function of forcing frequency, for a variety of tubing lengths. Reproduced from [4]; Figure 5.

amplitude of the oscillation. Numerical solutions of the forced damped equations reveal that resonances can occur at one or both of the linear frequencies, depending on the precise circumstances. The amplitude of these resonances can be greater than that implied by the forcing, so the magnitude of gusts at these resonant frequencies may be overestimated. The model is capable, with some tuning of the unknown parameters, of reproducing the results of previous laboratory investigations into these resonances.

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