Proceedings of the ASME 2017 36th International Conference on Ocean, Offshore and Arctic Engineering
OMAE2017
June 25-30, 2017, Trondheim, Norway

OMAE2017-61516

RESPONSE VARIABILITY IN FLEXIBLE CYLINDER VIV MODEL TEST DATA

Themistocles L. Resvanis
Massachusetts Institute of Technology
Cambridge, MA, USA

J. Kim Vandiver
Massachusetts Institute of Technology
Cambridge, MA, USA

ABSTRACT
This paper presents some results from the 2011 SHELL tests at the MARINTEK basin. The tests involved towing densely instrumented 38m long flexible cylinders at Reynolds numbers up to 220,000. The main objective it to present the experimental results in a manner that describes the response variability that exists in the measured response data.

Despite the fact that VIV is known to be a stochastic process, this is rarely addressed in the literature and currently there is no framework or 'best-practice' in the VIV community that can address statistically non-stationary data. In this paper, the experimental measurements are treated like non-stationary time-series and all statistical quantities which are typically of interest are computed with the use of short duration moving windows (or time-gates). A novel way of plotting and presenting VIV response data for flexible cylinders is introduced that is capable of revealing the inherent variability that exists in the cylinder's response.

INTRODUCTION
The examples chosen and discussed in this paper demonstrate that the Vortex-Induced Vibration (VIV) response amplitude of flexible cylinders can show considerable variation when exposed to steady flows even in carefully controlled laboratory settings. This variation in response can take two forms:

- In the first case, all sensor locations on the flexible cylinder have the same dynamic response characteristics but these can vary in time.
- In the second case, different portions of the flexible cylinder show very different response characteristics at the same instance in time.

It is important to note that the above observations are not new to researchers in the VIV community and the objective of this paper is not to present the above findings as novel findings but rather to emphasize the importance of keeping the above observations in mind when analyzing the data collected in a typical VIV test campaign.

The stochastic nature of the measured time-series quantities has serious implications when choosing the time-section or time-record for further analysis. It is shown that using the entire time-section or attempting to use a statistically stationary time portion will not reveal or does not necessarily coincide with the largest VIV response and most damaging conditions. This paper proposes a novel way to plot the VIV response of a flexible cylinder by making use of the 'RMS response envelope' which is capable of illustrating the variability in the response in a concise manner.

A typical VIV model testing campaign can have many different objectives that vary based on the specific problem being investigated (*e.g.*, evaluation of suppression devices, buoyancy distribution, *etc.*) but it invariably involves measuring the cylinder's response at many different towing speeds. For rigid, elastically mounted cylinders this is done in order to span the entire lock-in range (*i.e.*, synchronization region) whereas on flexible cylinders one wants to characterize the response of many different modes over a range of speeds.

Current practice for analyzing the time-series data collected during each test run calls for identifying the initial and last ~20% of each time-series recorded which is then discarded or dismissed due to 'transient behavior(s)'. The middle portion of the time-series that remains, is then treated as stationary data and the desired statistical quantities are computed.

This decision to treat the time-series as stationary data is often made despite clear indications to the contrary simply because the topic is not usually addressed in the literature and currently there is no framework or 'best-practice' in the VIV community that can address statistically non-stationary data. The response amplitudes and curvatures (or stresses or strains) are thus typically reported as single values for each test and as this paper will show these values can be significantly different from the maximum observed values.

To date, the only commonly accepted practice for accounting for the variability in the observed VIV response data has been the use of rain-flow counting methods for estimating the accumulated damage rather than relying on various closed form expressions for calculating the damage rate (or remaining fatigue life) based on the RMS or standard deviation of the stress time-series. Baarholm *et al.* (2006) include an insightful comparison of the rainflow-counted damage rate with the Rayleigh-distributed damage formulas. The rainflow-counting approach is a very satisfactory method of accounting for the effect of the response variability on the fatigue life or damage rate quantities since it can handle both the amplitude and frequency modulation that is often present in the recorded time-series.

The damage rate is only one of the many response quantities that are typically of interest when conducting VIV model tests or field experiments where response frequencies, response amplitudes or accelerations, stresses, drag coefficients, *etc*. are often investigated. There is a case to be made for studying the variability in all of these quantities especially when trying to benchmark and improve the quality of VIV prediction programs. This is because VIV prediction programs are often benchmarked against the available measurements by comparing the predicted damage rates with the damage rates measured during the tests. The problem with this approach is that the predicted damage rate depends on both the predicted frequency and the predicted stress (and hence the response amplitude and predicted mode number) and as such, various combinations of high frequencies and small response amplitudes or low frequencies and large response amplitudes can lead to similar predicted damage rate values. Additionally, better response amplitude predictions will allow for more accurate drag load estimates since most of the accepted VIV drag amplification formulas have a strong dependence on the VIV response amplitude.

The most notable exception to the previously discussed practice of treating the measured data as stationary time-series was the investigation undertaken by Modarres-Sadeghi *et al.* (2011) who looked at the VIV response of flexible cylinders and concluded that the response can usually be classified as *type-1* or *type-2* based on the observed response. VIV response which is (almost) monochromatic and periodic is classified *type-1* (or quasi-periodic behavior) whereas VIV which shows strong narrow-banded response is termed *type-2* (or chaotic behavior). The authors used the phase-plane (among other tools) to identify whether an observed VIV response is best classified as *type-1* or *type-2*. The authors observed three types of behavior when analyzing the 38mNDP dataset (high mode number tests):

- cases where the entire signal is mostly *type-1*
- cases dominated by *type-1* response with occasional bursts of type-2 response
- cases entirely dominated by *type-2* response where it is impossible/or very hard to even identify a small time-section with *type-1* response.

The analysis of the 38m SHELL dataset presented in this paper confirms many of the observations that Modarres-Sadeghi *et al.* (2011) made but emphasizes the important observation that different portions of the flexible cylinder can show very different response characteristics at the same instance in time. Which means that the portion of a time-series that seems statistically stationary and suitable for analysis for one end of the riser model may not be at all appropriate for the other end of the riser model.

VIV is by its own nature a stochastic process and treating it deterministically will inevitably mask many interesting and fascinating features. This paper investigates some aspects of this behavior by presenting some brief statistics concerning the observed VIV response.

Mandel (1984) offers a very convincing argument for the statistical analysis of experimental data. His opinion is that the purpose of the analysis is to confirm the presumed linearity (or other underlying trend) of an identified relationship and obtain the best values for the parameters characterizing the relationship by investigating this lack of definitiveness and thus ascertain the limits of validity of the conclusions drawn from the experiment.

Furthermore, statistical analysis should be useful as a diagnostic tool. Causality is hard to determine, but from a practical standpoint one could start asking whether the variability in the response will get smaller if:

- The signals appear to be stationary in time.
- The test is conducted at the exact reduced velocity that results in maximum response.
- There is no mode-switching.
- There are no fluctuations in towing velocity or little large scale turbulence in the incident flow.

Eliminating each one of the above could potentially decrease the extent of the response variability until it reaches the point where it is entirely due to the stochastic nature of VIV and nothing else. The experimentalist often has little control over some of the factors listed above and therefore it is not easy or straightforward to address all of them when designing VIV model testing experiments.

One of the aims of this paper is to convince the reader and the experimentalist that it is worthwhile to attempt to study the variability in the observed VIV response rather than proceeding with an analysis of the measurements that will mask it.

DESCRIPTION OF EXPERIMENTS

The 38*m* SHELL experiments were conducted in the spring of 2011 at MARINTEK's ocean basin on behalf of SHELL International Exploration and Production Co. The experiments involved towing three densely instrumented flexible cylinders, of different diameters, in uniform and sheared currents. The full test matrix included more than 430 runs which tested the effects of fairings, strakes, staggered buoyancy and marine growth on riser response in uniform and linearly sheared currents.

An interesting feature of this data set was the very large range of Reynolds numbers covered while testing the three different pipes. Towing velocities ranged from 0.25*m/s* to 3.45*m/s* which correspond to a Reynolds number range from 5,000 to 220,000 in sheared flows and up to 150,00 in uniform flows.

More details on the experimental set-up can be found in Lie *et al.* (2012) and MARINTEK (2011). The results from these tests have already been published in a series of papers over the past few years, see Rao *et al*. (2012, 2013, 2014), Resvanis *et al.* (2012, 2016) and Wu *et al.* (2014, 2015, 2016). This paper will only address the response of the two larger diameter cylinders in uniform and sheared flows with no suppression devices attached.

Table 1. Cylinder Properties

	Pipe 2	Pipe 3
Length	38 *m*	38 *m*
Outer Diameter (Hydrodynamic Dia.)	30 *mm*	80 *mm*
Optical Diameter (Strength Diameter)	27 *mm*	27 *mm*
Inner Diameter	21 *mm*	21 *mm*
EI	572.3 Nm^2	572.3 Nm^2
E	3.46e10 N/m^2	3.46e10 N/m^2
Mass in air (with contents)	1.088 *kg/m*	5.708 *kg/m*
Mass in water (with contents)	0.579 *kg/m*	0.937 *kg/m*
Mass ratio	1.54	1.14

The medium and large diameter cylinders, Pipes 2 & 3 respectively, had curvature (strain) measured at 30 different locations along the length using fiber optic Bragg strain gauges in both the cross-flow (CF) and the in-line (IL) directions. The accelerations were measured at a further 22 locations along the riser model using accelerometers in both the CF and IL directions. All sensors were sampled at a frequency of 1200*Hz*. The largest diameter pipe was simply the medium sized pipe with a clam-like plastic shell, 25*mm* thick, surrounding it. For the medium and large pipes, the curvature was measured at a distance of 13.5*mm* from the neutral axis and the fiber optic cable was then covered by a silicon sheet 1.5*mm* thick.

Damping tests conducted in air for all three cylinders yielded structural damping ratios of ~0.5-0.7 of critical damping.

ANALYSIS

In order to capture the unsteady or non-stationary behavior, all response statistics, like the RMS dimensionless amplitude (*A/D*), the RMS curvature, *etc*. are computed from within a 'moving window' which passes through the entire data record. A typical window length that was used, was one corresponding to 5 vortex shedding periods ($j=5$), with the shedding frequency determined using the flow speed, U, the hydrodynamic diameter, D, and a Strouhal number of $St=0.15$ (*i.e.*, the dimensionless response frequency in this context).

Window length (in seconds) of the 'moving window':

$$T = j\, T_{vortex} \qquad \text{eq.1}$$

where T_{vortex} is the vortex shedding period defined as:

$$T_{vortex} = \frac{1}{f_{vortex}} = \frac{D}{U\, St} \qquad \text{eq.2}$$

Now the moving or running mean of a time varying signal $a(t)$ can be defined as:

$$\mu_a(t) = \frac{1}{T}\int_{t-T/2}^{t+T/2} a(\tau)d\tau \qquad \text{eq. 3}$$

Similarly, the moving or running standard deviation of the signal $a(t)$ can be defined as:

$$\sigma_a(t) = \sqrt{\frac{1}{T}\int_{t-T/2}^{t+T/2}[a(\tau)-\mu_a(\tau)]^2 d\tau} \qquad \text{eq. 4}$$

All time-series responses discussed in this paper are zero-mean quantities and as such the root mean square (RMS) is identical to the standard deviation of the time-series.

The various time-series quantities that are discussed in this paper are: the curvature at every fiber-optic strain gauge along the model and the response amplitude at every location along the model.

For the medium and large sized pipes, the response amplitude can be readily computed after integrating the accelerometer signals at every accelerometer location. To account for the possibility, that the spatial location where the maximum response occurs, falls between two measurement locations, a modal reconstruction along the lines of Lie & Kaasen (2006) was performed for each test case. The reader is referred to Resvanis *et al.* (2012) for an example of the good agreement between the modal reconstructed response amplitudes and the displacements measured at each accelerometer location.

The original motivation for treating the collected data as non-stationary time-series arose from the need to analyze a special subset of the SHELL dataset that involved response measurements under time-varying flows which is described in Resvanis (2014) and Resvanis *et al.* (2015).

RESULTS AND DISCUSSION

Before proceeding and introducing the 'RMS response envelope' that can readily summarize the response variability that exists during a VIV model test, two different tests will be discussed because they are ideal candidates for illustrating the shortcomings of the typical or commonly used approaches in VIV measurement analysis.

Test 3002 involved towing the 30*mm* diameter cylinder (Pipe 2) in a uniform flow of 0.5*m*/s and Fig. 1 shows several displacement time histories at 6 different accelerometer locations; the top three plots correspond to neighboring accelerometers near one end of the flexible cylinder whereas the lower three plots correspond to three neighboring accelerometers on the other end. The phase-plane corresponding to each time history is shown next to it. The displacements and velocities shown have been obtained by integrating the accelerometer signals in the frequency domain.

The blue line in the phase-plane corresponds to the entire time signal of the test, whereas the red lines corresponds only to the time-section identified in red color. Just by observing the time-histories colored in red one could conclude that the data looks very periodic and stationary, but this is further reinforced by the phase-planes shown in red. One would expect a constant amplitude sinusoidal signal to have a phase plane that looks like a circle or an ellipse (depending on the axis' scaling). The additional kinks present in the red ellipses are due to the 3X and 5X contributions, *i.e.*, the higher harmonics. For the time-section identified in red color, between the 63rd and 78th seconds, one can easily conclude that the VIV response is dominated by *type-1* or quasi-periodic behavior.

Test 3002 is an example of VIV response where one can indeed identify a statistically stationary time-section that is suitable for all sensor locations on the flexible riser model and that can be used for further analysis. However, it will be shown that this type of response, where every point of the entire structure is behaving in a very specific manner is the exception and not the norm when analyzing the 38m long SHELL dataset.

Test 3003, shown in Fig. 2, is much more typical of the behavior observed in the SHELL dataset. The testing conditions for Test 3003 were very similar to Test 3002 discussed previously, with the only difference being a slightly higher towing speed of 0.6m/s, yet by observing the time-histories in Fig.2, it is very difficult to determine a time-section where all points along the flexible cylinder behave in a similar manner.

Specifically, the time-section identified in red color would appear to be a good time-section to use for analysis for one end of the riser model (the lower thee plots corresponding to sensors 17, 18 & 19) with the response characterized by constant amplitude periodic oscillations. However, during the same time, it should be clear that the time-section identified in red color is characteristic of chaotic response for the other end of the cylinder (top three plots).

Figure 3, once again shows the displacement time-histories from Test 3003, but now a time-section characterized by type-1 (quasi-periodic) oscillations is chosen for the opposite end of the cylinder which had previously been characterized by a strong chaotic response. The behavior identified in Test 3003, ***i.e.*****, that different parts of the riser model can have very different response characteristics at the same instance in time**, is very typical of what is seen throughout the SHELL dataset and other flexible cylinder VIV measurements. This fact makes identifying suitable stationary time-sections very hard or impossible at times and a different approach might be more suitable. This, of course, is not a new observation and the VIV community has over the years, given different names to certain specific features such as:

- Time-sharing, when the response frequency at which lock-in is occurring changes or jumps to neighboring natural frequencies.
- Space-sharing, when the response at different (often well separated) sections of a riser seem to be responding at different frequencies.
- More recently, the response has been characterized as standing wave, travelling wave and mixed when it is hard to separate which if the two is dominant.

The examples discussed up to this point were not chosen to dismiss any of the above characterizations but rather to reinforce the fact that it is rarely sufficient to look at a single or even a couple of neighboring sensors when choosing which portion of the time-series to analyze in the data processing phase.

Instead of trying to identify stationary time-sections by looking at a handful of sensors and then subsequently using that limited data for analysis it is more meaningful to use as much of the time-series as possible but analyze it with tools more appropriately suited to non-stationary time-series. These tools can include but are not limited to wavelets, Hilbert-Transforms, moving-windows, *etc.*

The variation in the response frequency is a topic that is typically covered in the literature and will not be discussed further here, instead the remaining portion of this paper focuses on presenting the variability in the measured response amplitudes and stresses which are topics that are rarely discussed.

It is very common when reporting VIV test data to refer to or plot the RMS (or standard deviation) of the response amplitudes or the stresses along the cylinder's length. This is straightforward to depict graphically if there is only one value of the response quantity to show at each measurement position along the cylinder or model but becomes increasingly more complicated after treating the data as a non-stationary time-series since there is now a range of possible values for the response quantities of interest.

Figure 4 is a novel way of presenting non-stationary VIV response data through the use of the 'RMS response envelope'. This single figure includes all the variability observed in the VIV response during Test 3002. It is created in the following way:

- The grey-green envelopes shown are created by identifying the largest and smallest RMS response at each location after passing through the entire time-series using a 'moving window'. This envelope of RMS response does not include any information relating to the time instance when the largest or smallest RMS response occurred but it brackets every response calculated during the ~72 second test.
- The red line is the RMS response using the ENTIRE time--section instead of a moving 5 second window; this is similar to what would be typically shown in the literature as the VIV response along the riser for a given test.
- The dashed lines correspond to the result displayed by the red line described above ±1 standard deviation from the ensemble of the 'moving RMS' values calculated at every point. For most of the duration of the test, the RMS response amplitude (top plot) or RMS response stress (bottom plot) at each position along the cylinder length will take a value between the two dashed blue lines.

Figure 5, shows this variability at a specific position situated at a dimensionless distance of x/L~0.91 along the riser as a histogram of all possible RMS response amplitudes, computed using a 'moving window' that passes through the entire time record during which the towing speed was constant, roughly between the 37th and 109th seconds. The plot indicates that for a large portion of time, at this specific position along the span, the RMS amplitude was approximately 0.63D, but in fact it varied anywhere between $0.47 < A/D < 0.81$.

This variability in the response quantities (amplitude or strain/curvature) is an inherent feature of VIV and the aim of the 'RMS response envelope' and the example chosen is to demonstrate that it is not sufficient to analyze data by blindly trimming the beginning and ending of the time-series and then proceeding assuming that it is stationary, in fact, doing so can lead to over or under estimating the response amplitudes at certain locations along the riser model by 50%.

For completeness, the response during the short stationary time-section identified in Fig. 1 between the 63rd and 78th second is shown in Fig. 7. Notice how much 'tighter' the response envelope (shaded grey-green) and the ±1 standard deviation lines (dashed blue) are in Fig. 7 compared to Fig. 4. Also note, how much narrower the band of possible RMS amplitudes is in Fig. 6 when compared to Fig. 5 discussed above. Therefore, only if one is fortunate enough to identify a statistically stationary portion of the time-series that is applicable to all sensor locations on the riser model would the traditional way of computing response quantities be representative of the observed conditions.

This is a field of active research and clearly there is room to improve on the techniques suggested in this paper. For example, reporting and showing the ±1 or ±2 standard deviation lines is very meaningful for a probability distribution that resembles a Gaussian distribution similar to Fig. 6 but their interpretation is more challenging for a bi-modal distribution shown in Fig. 5.

As discussed earlier, when analyzing experimental VIV measurements on flexible cylinders, it is extremely uncommon to find stationary time-sections where the entire riser or model is behaving in a similar manner at the same time. If one chooses to only analyze the tests or portions of a test where the measured time-series satisfied stationarity they would be left with only a handful of tests out of the hundreds that are typically included in a VIV test campaign. It is much better to accept that VIV (especially on flexible cylinders) is stochastic by nature and try to find ways that capture some of the variability in the observed response.

All tests from the SHELL campaign have been reanalyzed treating the data as non-stationary time-series and response variability similar to what was shown in Fig. 3 is observed to be the norm rather than the exception. Because of space limitations and in the interest of brevity, the remaining portion of the paper will only discuss the response variability observed for the position along the riser model that experienced the largest response during each test.

Figures 8 and 9 show the maximum response amplitude for the 30*mm* and 80*mm* diameter cylinders respectively. In these figures each data point represents the spatial or spanwise maximum response amplitude along the riser model that was observed during each test. This quantity had been computed using the entire time-record. On top of each data point, 'error bars' have been added that represent ±1 standard deviation of the response variability at that same location calculated using a 'moving window' that passed through the time-series. In this context the 'errors bars' drawn represent the magnitude or extent of the response's variability in each test and reflect the most probable values that the maximum response amplitude could have taken if different time-sections had been analyzed. If the probability distribution of the reported RMS values at each location (see Figs 5 & 6) resembled a Gaussian distribution, then the 'error bars' corresponding to ±1 standard deviation would bracket ~68% of all possible RMS response amplitudes observed during each test.

These figures have been included here to demonstrate that the large response variability observed during Test 3002 shown in Fig. 4 was not unique to that specific test run, but rather is an inherent feature of VIV on flexible cylinders exposed to steady flows even when tested in carefully controlled laboratory conditions. Only a small number of tests in the entire test matrix showed small amounts of response variability as indicated by the very tight 'error bars' on a very small number of data points in Figs. 8 & 9.

Another reason for including these figures here is to confirm the Reynolds number effects that had been reported earlier by Resvanis *et al.* (2012) that showed that the maximum response amplitude in the subcritical Reynolds region is Reynolds number dependent. This is best observed by looking at the uniform flow test for the 30*mm* diameter flexible cylinder, where the lowest speed corresponds to a Reynolds number of ~8,000 and the highest speed corresponds to a Reynolds number of ~68,000. Despite the large variability that is possible at each test speed there is a very obvious trend of increasing response amplitude with increasing Reynolds number. This is much harder to identify in the data corresponding to the 80mm diameter cylinder because it responded at much lower mode numbers and the unfavorable reduced velocity effects can be very pronounced at certain speeds.

CONCLUSIONS

The main objective of this paper was to demonstrate the importance of accounting for the non-stationary behavior of VIV response data when analyzing model response data. The VIV response amplitude of flexible cylinders can show considerable variation when exposed to steady flows even in carefully controlled laboratory settings. The variation in the response of flexible cylinders can take two forms:

- In the first case, all sensor locations on the flexible cylinder have the same dynamic response but this can vary in time (The entire cylinder is undergoing quasi-periodic vibrations or the entire cylinder is exhibiting chaotic behavior)
- In the second case, different portions of the flexible cylinder show very different response characteristics at the same instance in time.

This complicated behavior makes it very hard for the analyst to choose a statistically stationary time-section that is suitable for all sensor locations along the riser model. Electing to treat all the recorded data as non-stationary time-series bypasses this difficulty. By computing the desired statistical response quantities from within 'moving windows' that pass through the entire time-series, the analyst can ensure that the inherent variability in the response quantity under investigation has been properly accounted for.

The 'RMS response envelope' envelope is shown to be a convenient method of depicting the response variability that can exist within a single test run. The most important conclusion of this paper is the fact that the VIV response of flexible cylinders in steady flows (*i.e.*, at constant towing speed) is anything but steady and deterministic.

There are at least two reasons why the VIV community should start focusing on the VIV response variability apart from the traditionally employed rain-flow counting of damage rates. The first is that quantifying this variability could be used as a diagnostic tool in attempts to improve how these model tests are conducted. The second reason is that quantifying the response variability can be of great assistance in guiding efforts to improve VIV prediction software. These large variations in observed response amplitudes can be very important when comparing or benchmarking VIV prediction programs against experimental measurements. The majority of popular VIV prediction programs that exist today are deterministic yet they are being compared with experimental measurements that are known to be stochastic. Moreover, programs parameters are often over-tuned to match specific experimental measurements while overlooking that there is a range of correct or acceptable experimental response values for each test condition.

ACKNOWLEDGEMENTS

The authors acknowledge SHELL International Exploration and Production Co. for providing access to the experimental data and the SHEAR7 JIP members (AMOG, BP, Chevron, ExxonMobil, SBM, Shell, Statoil & Technip) for supporting this research.

REFERENCES

[1] Baarholm, G.S., Larsen, C.M., & Lie, H., 2006, *On Fatigue Damage Accumulation from In-Line and Cross-Flow Vortex-Induced Vibrations*, Journal of Fluids and Structures, 22:109-127

[2] Modarres-Sadeghi, Y., Chasparis F., Triantafyllou, M.S., Tognarelli, M., & Beynet, P., 2011, *Chaotic Response is a Generic Feature of Vortex Induced Vibrations of Flexible Risers*, Journal of Sound and Vibration, 330:2565–2579.

[3] Mandel, J., 1984, *The Statistical Analysis of Experimental Data*, Dover Publications, New York

[4] Lie, H., Braaten, H., Jhingran, V.G., Sequeiros, O.E & Vandiver, K., 2012, *Comprehensive Riser VIV Model Tests in Uniform and Sheared Flow*, OMAE2012-84055

[5] MARINTEK, 2011, *Shell Riser VIV Tests Main Report*, No. 580233.00.0, Trondheim, Norway

[6] Rao, Z., Vandiver, J.K, Jhingran, V. & Sequeiros, O., 2012, *The Effect of Exposure Length on the Vortex Induced Vibration of Flexible Cylinders*, OMAE2012-83272

[7] Rao, Z. & Vandiver, J.K., 2013, *VIV Excitation Competition Between Bare and Buoyant Segments of Flexible Cylinders*, OMAE2013-11296

[8] Rao, Z., Resvanis, T.L. & Vandiver, J.K., 2014, *The Identification of Power-In region in Vortex-Induced Vibration of Flexible Cylinders*, OMAE2014-24472

[9] Resvanis, T.L., Jhingran, V., Vandiver, J.K. & Liapis, S., 2012, *Reynolds Number Effects on the Vortex-Induced Vibration of Flexible Marine Risers*, OMAE2012-83565

[10] Resvanis, T.L., Rao, Z. & Vandiver, J.K., 2016, *Effects of Strake Coverage and Marine Growth on Flexible Cylinder VIV*, Journal of Offshore Mechanics and Arctic Engineering, vol.138

[11] Wu, J., Lie, H., Larsen, C.M. & Liapis, S., 2014, *In-Line and Cross-Flow Interaction of a Flexible Beam Subjected to Vortex Induced Vibrations*, OMAE2014-24559

[12] Wu, J., Decao, Y., Lie, H., Larsen, C.M., Baarholm, R.J., Jhingran, V. & Liapis, S., 2015, *On the Occurrence of Higher Harmonics in the VIV Response*, OMAE2015-42061

[13] Wu, J., Lie, H., Larsen, C.M., Liapis, S. & Baarholm, R., 2016, *Vortex-Induced Vibration of a Flexible Cylinder: Interaction of the In-Line and Cross-Flow Responses*, Journal of Fluids and Structures, 63:238-258

[14] Lie, H. & Kassen, K, 2006, *Modal Analysis of Measurements from a Large Scale VIV Model of a Riser in a Linearly Sheared Flow*, Journal of Fluids and Structures, 22:557-575

[15] Resvanis, T.L., 2014, Ph.D. Thesis: *Vortex-Induced Vibration of Flexible Cylinders in Time-Varying Flows*, Massachusetts Institute of Technology, Cambridge, MA

[16] Resvanis, T.L., Vandiver, J.K & Fu, S., 2015, *Ramp Tests: A Novel Approach to VIV Model Testing of Flexible Cylinders Using Continuously Varying Towing Speeds*, OMAE2015-42286

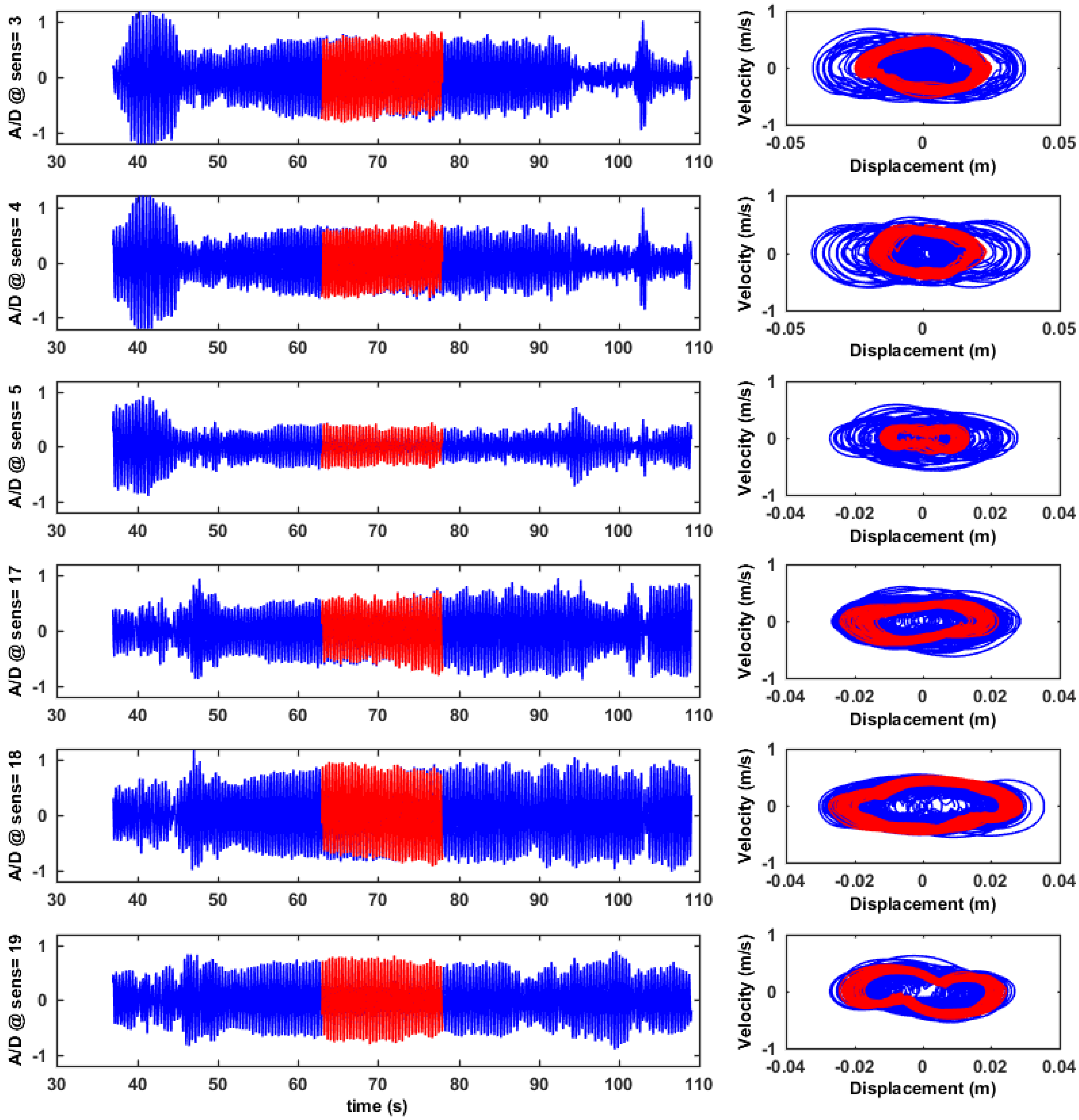


Figure 1: Time-histories and phase planes for Test 3002. A stationary portion of the time-series for all locations on the flexible cylinder is identified in red color between the 63rd and 78th seconds.

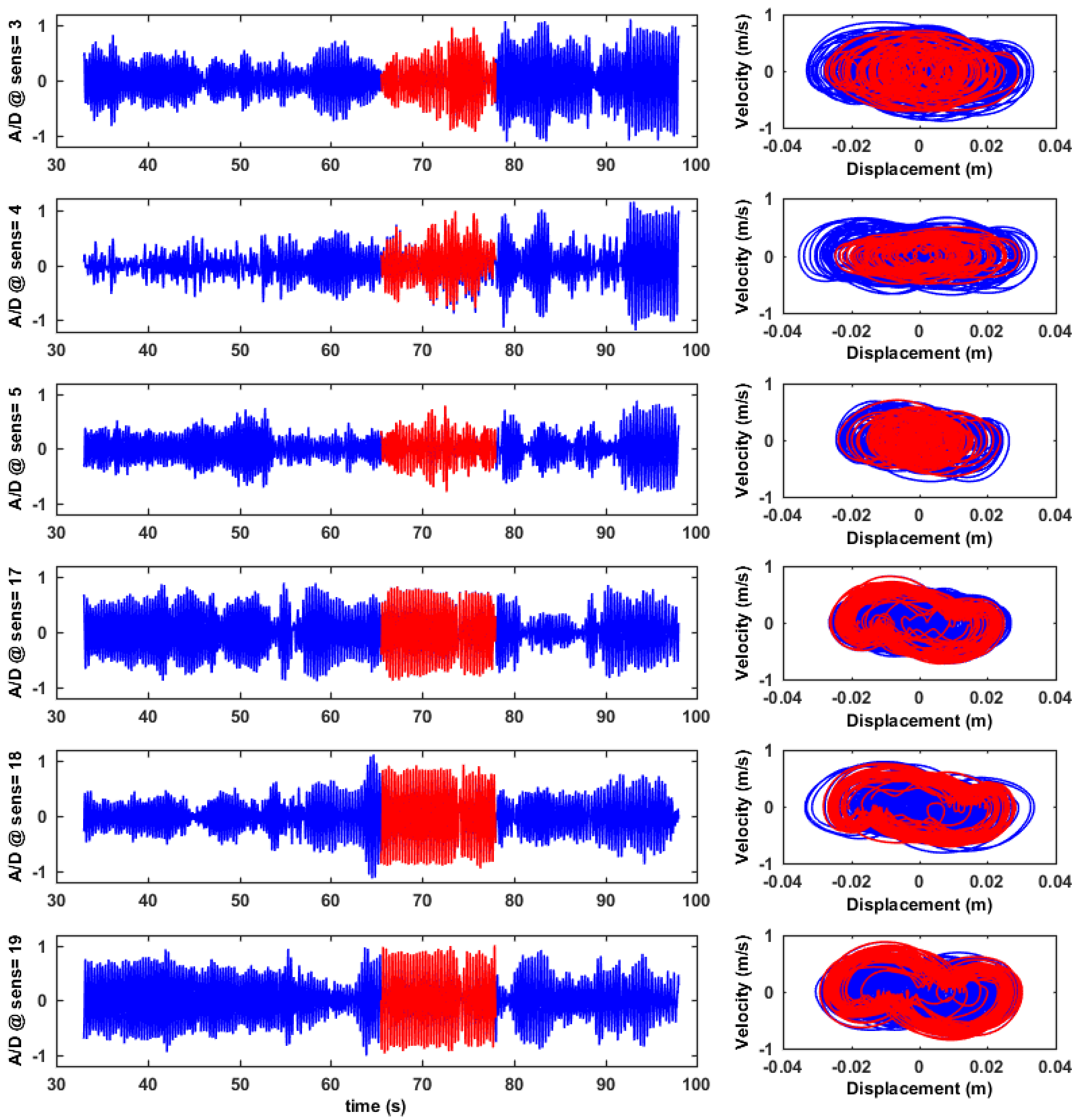


Figure 2: Time-histories and phase planes for Test 3003. The portion of the time-series highlighted in red between the 65^th^ and 78^th^ seconds is stationary only for the lower three plots which correspond to neighboring sensors on one end of the flexible cylinder.

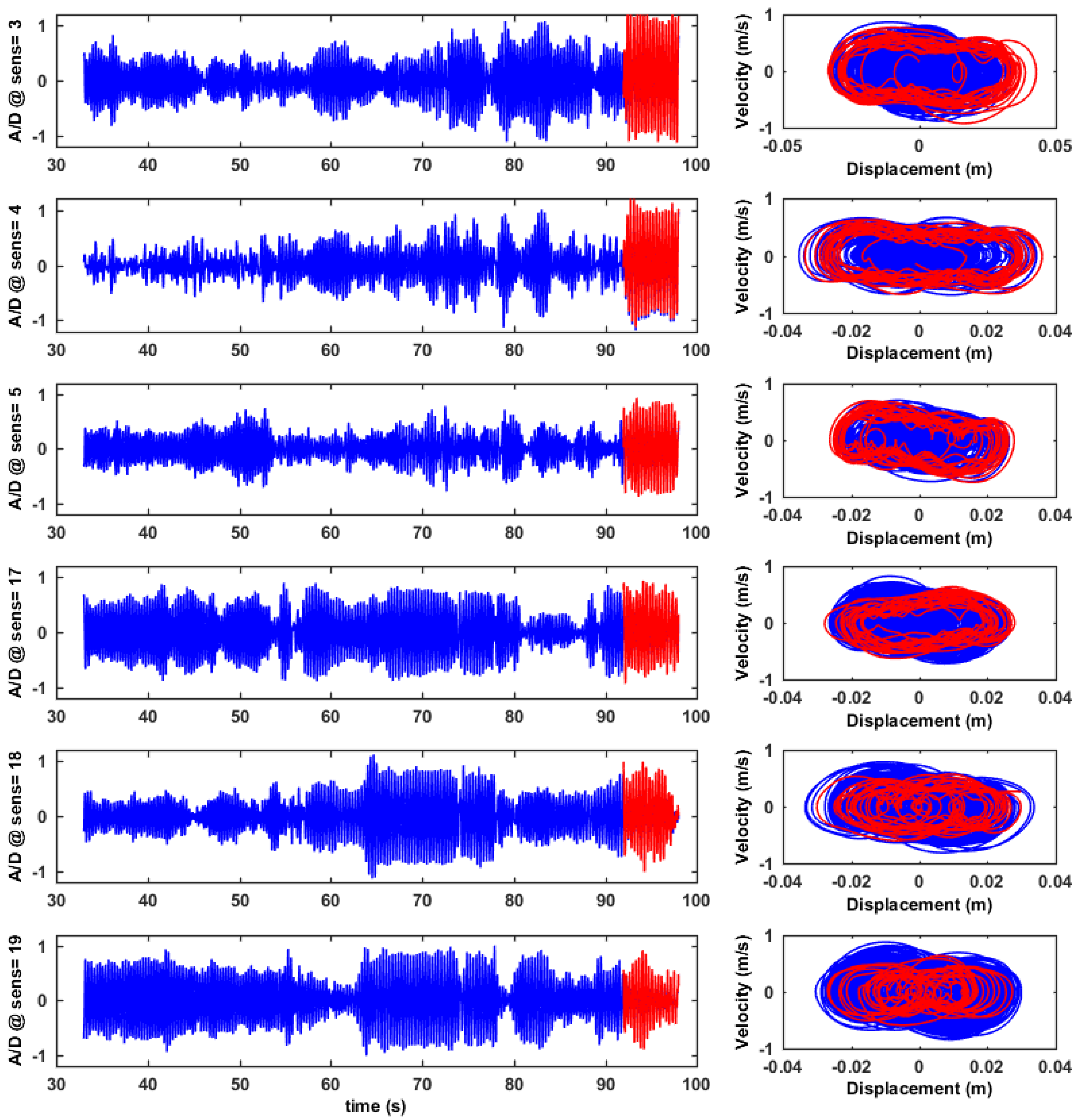
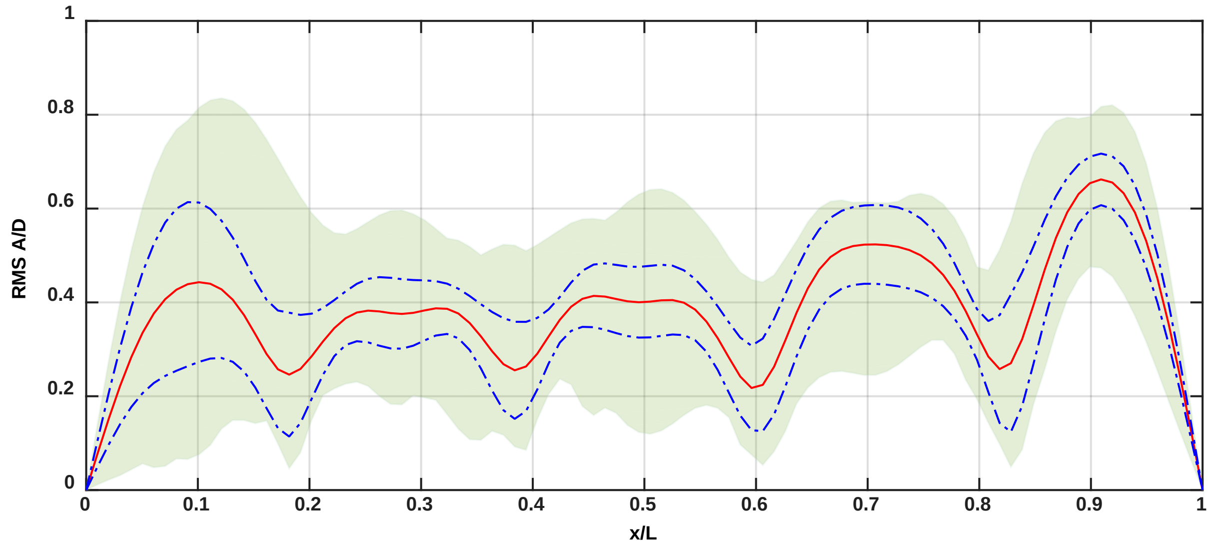


Figure 3: Time-histories and phase planes for Test 3003. The portion of the time-series highlighted in red between the 92nd and 98th seconds is stationary only for the upper three plots which correspond to neighboring sensors on the opposite end (compared to Fig. 2) of the flexible cylinder.



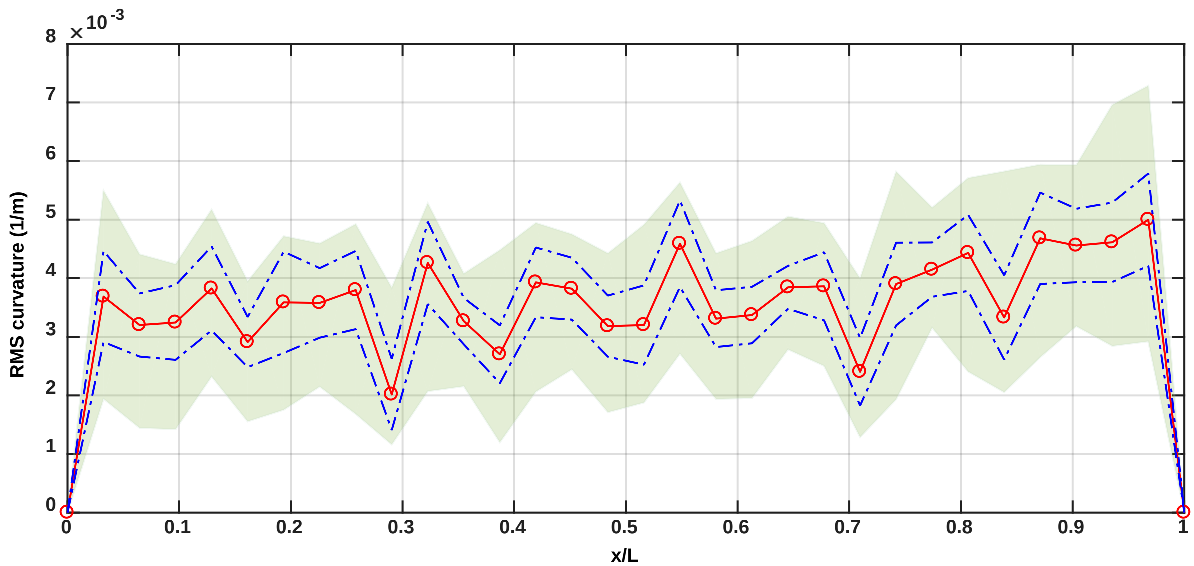


Figure 4: CF RMS A/D and Curvature (1/*m*) as calculated using a moving RMS for Test 3002 where the entire time-series between the 37th and 109th seconds was used.

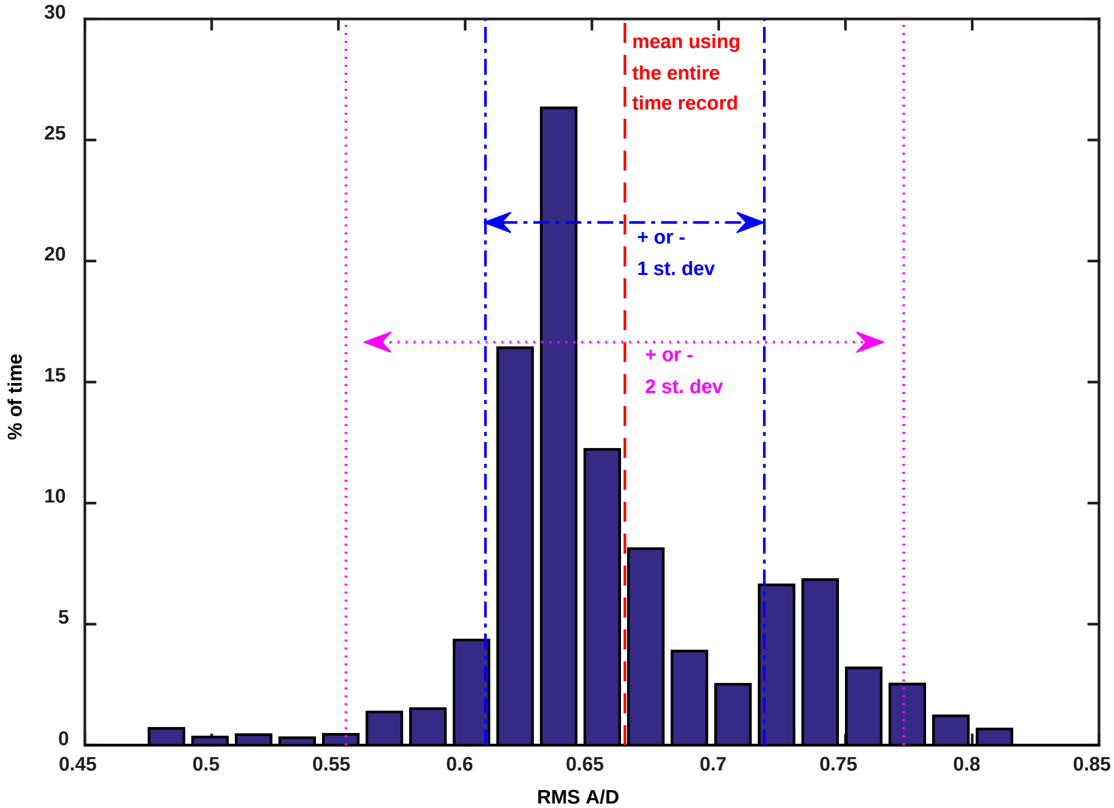


Figure 5: Variation in the RMS response at *x/L~0.91* for Test 3002 computed using a 'moving window' that passes through the entire time-series between the 37th and 109th seconds.

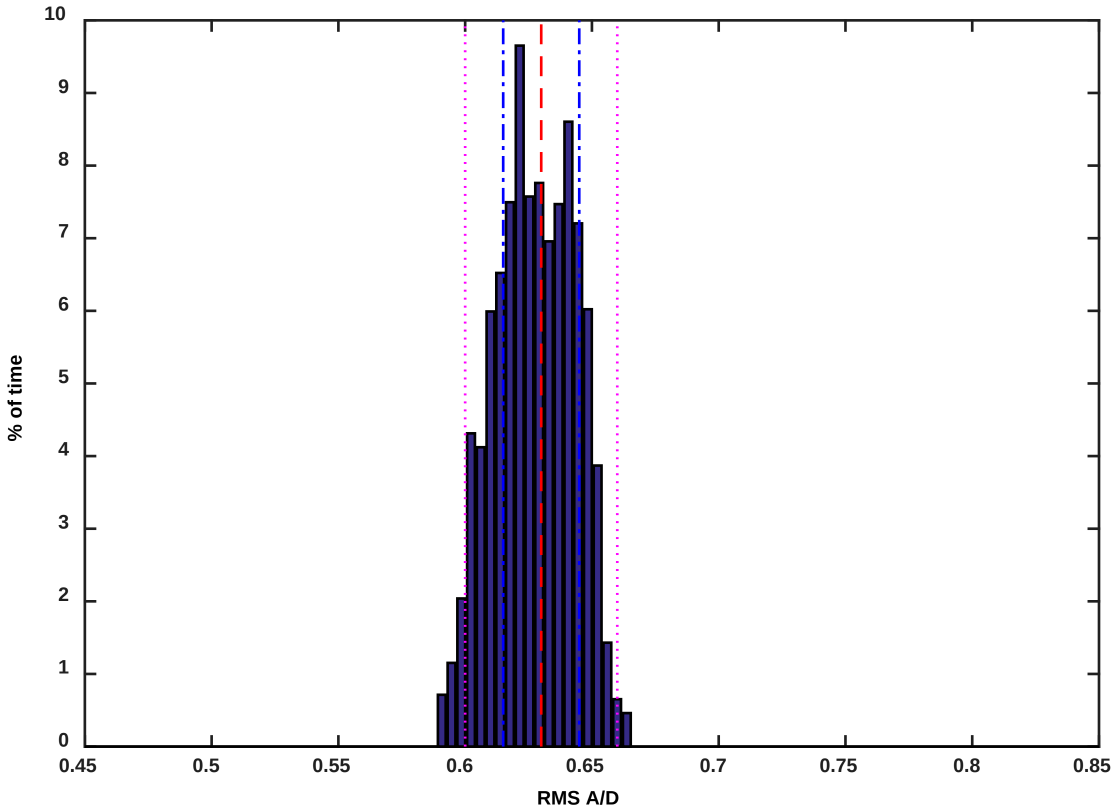


Figure 6: Variation in the RMS response at *x/L~0.9* computed using a 'moving window' that only passes through a short stationary time-section identified in Test 3002 between the 63rd and 78th seconds.

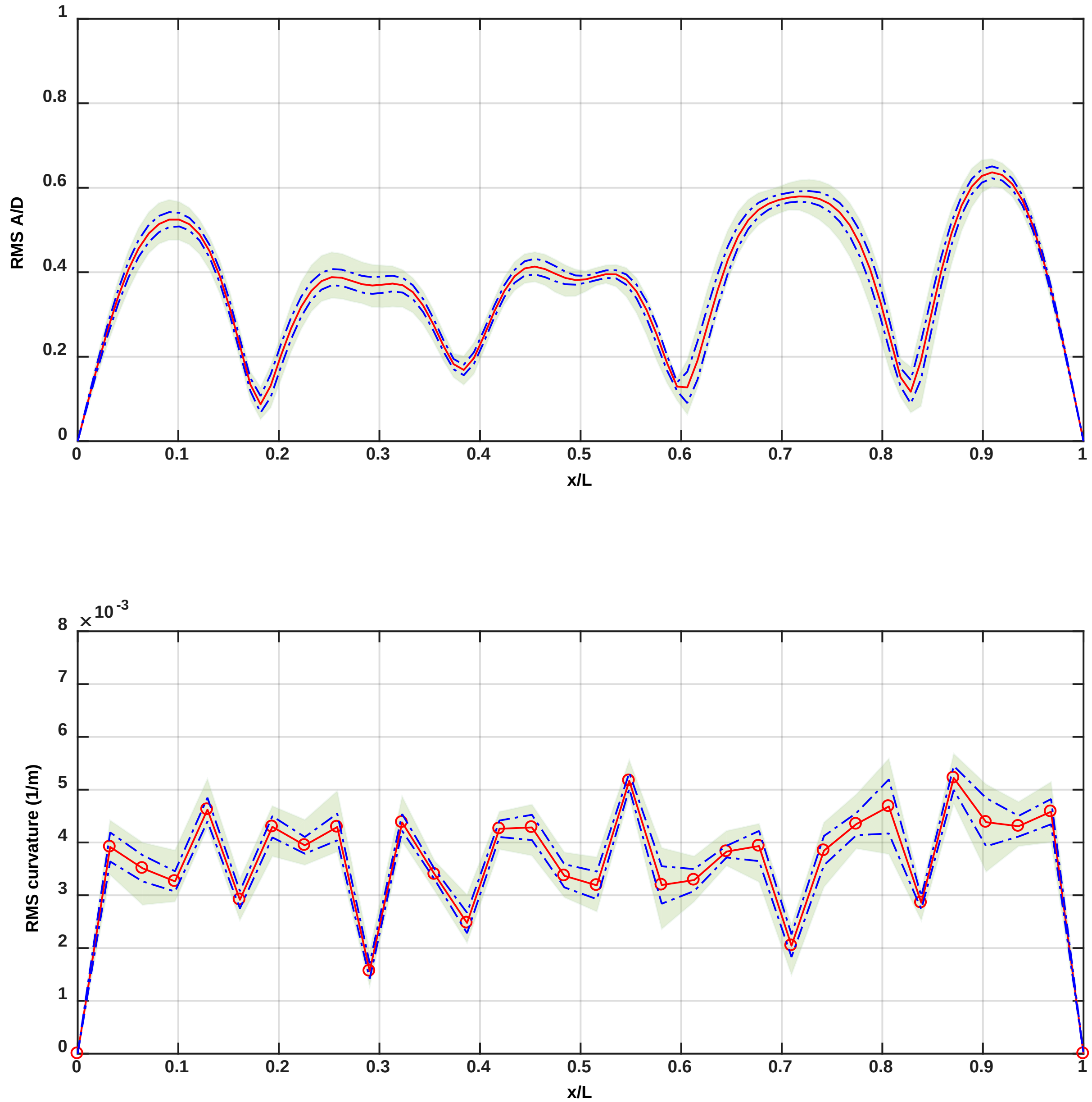


Figure 7: **CF RMS A/D and Curvature (1/*m*) as calculated using a moving RMS for a short stationary time-section identified in Test 3002 between the 63rd and 78th seconds.**

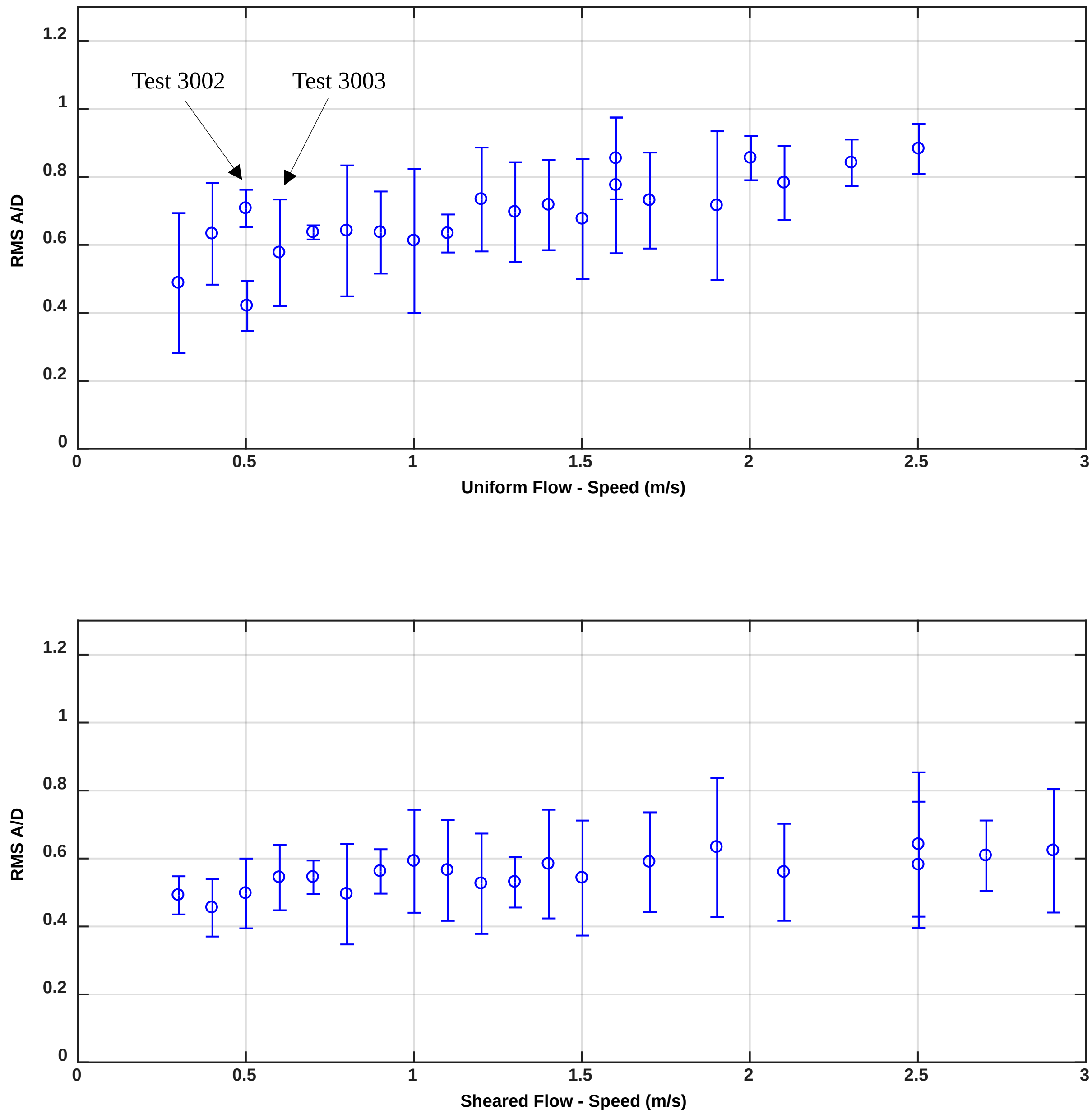


Figure 8: Maximum CF RMS *A/D* vs. towing speed for the 30*mm* diameter cylinder (Pipe 2)
(Data has been band-pass filtered around the appropriate 1X frequency for each test)

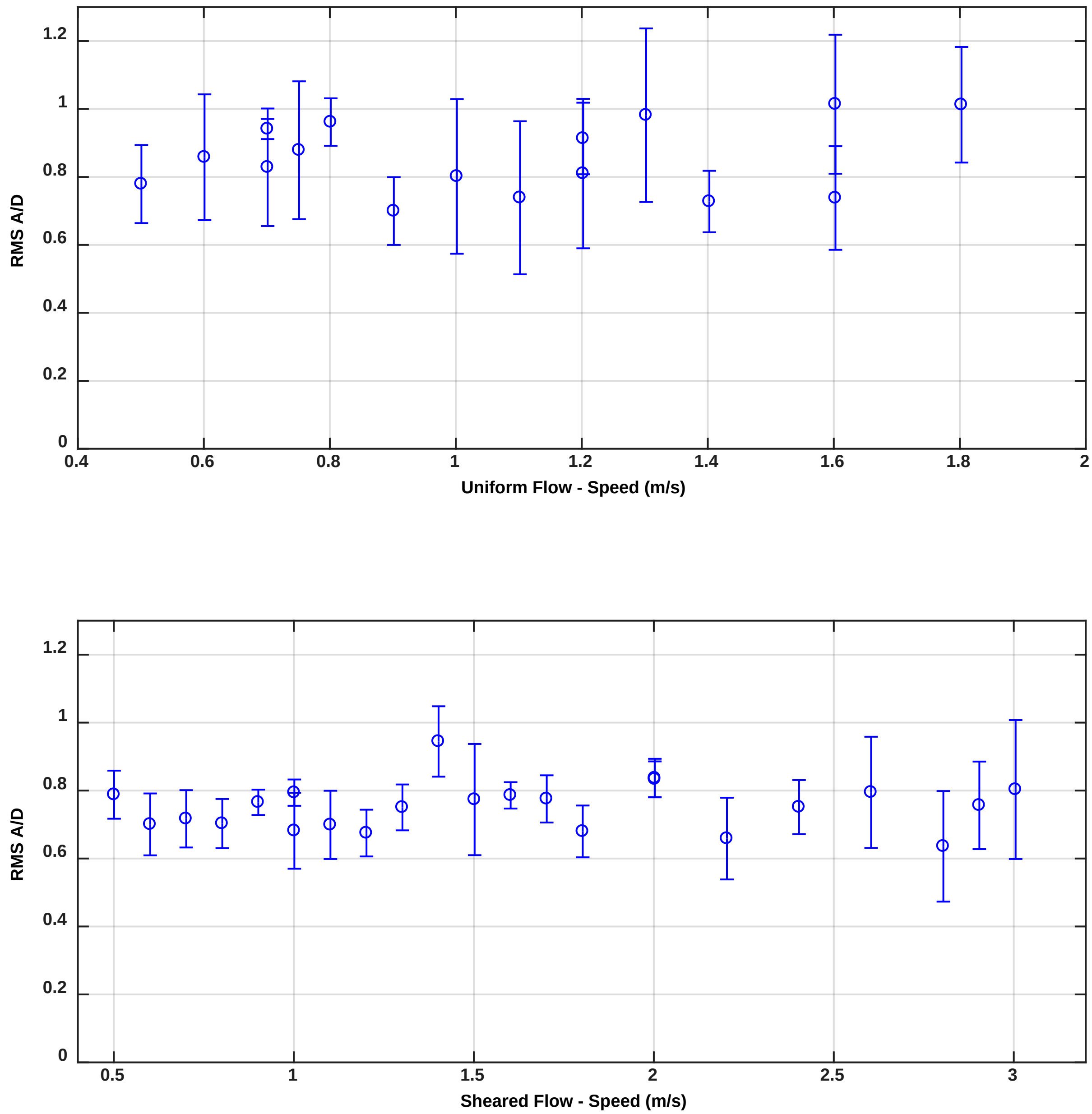


Figure 9: Maximum CF RMS *A/D* vs. towing speed for the 80*mm* diameter cylinder (Pipe 3)
(Data has been band-pass filtered around the appropriate 1X frequency for each test)